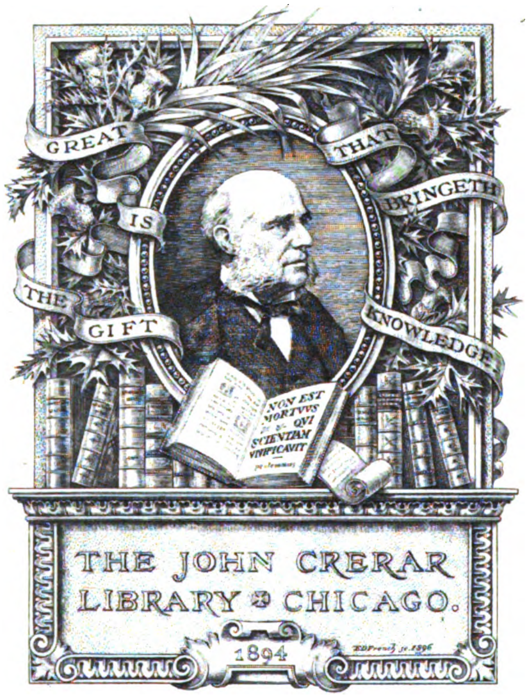
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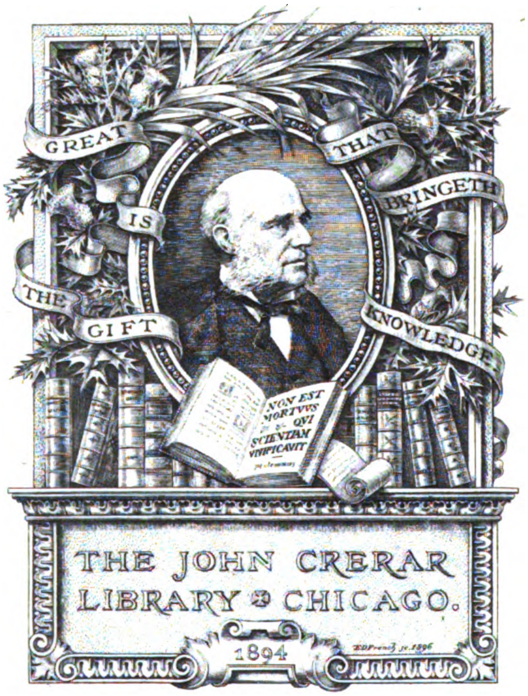
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THE ALEXANDERSON SYSTEM

FOR

RADIO TELEGRAPH AND RADIO TELEPHONE TRANSMISSION

Wireless Press
Incorporated
326 Broadway, New York

THE ALEXANDERSON SYSTEM FOR RADIO TELEGRAPH AND RADIO TELEPHONE TRANSMISSION

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TECHNICAL DESCRIPTION

OF THE

ALEXANDERSON SYSTEM

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RADIO TELEGRAPH AND RADIO TELEPHONE TRANSMISSION

By ELMER E. BUCHER

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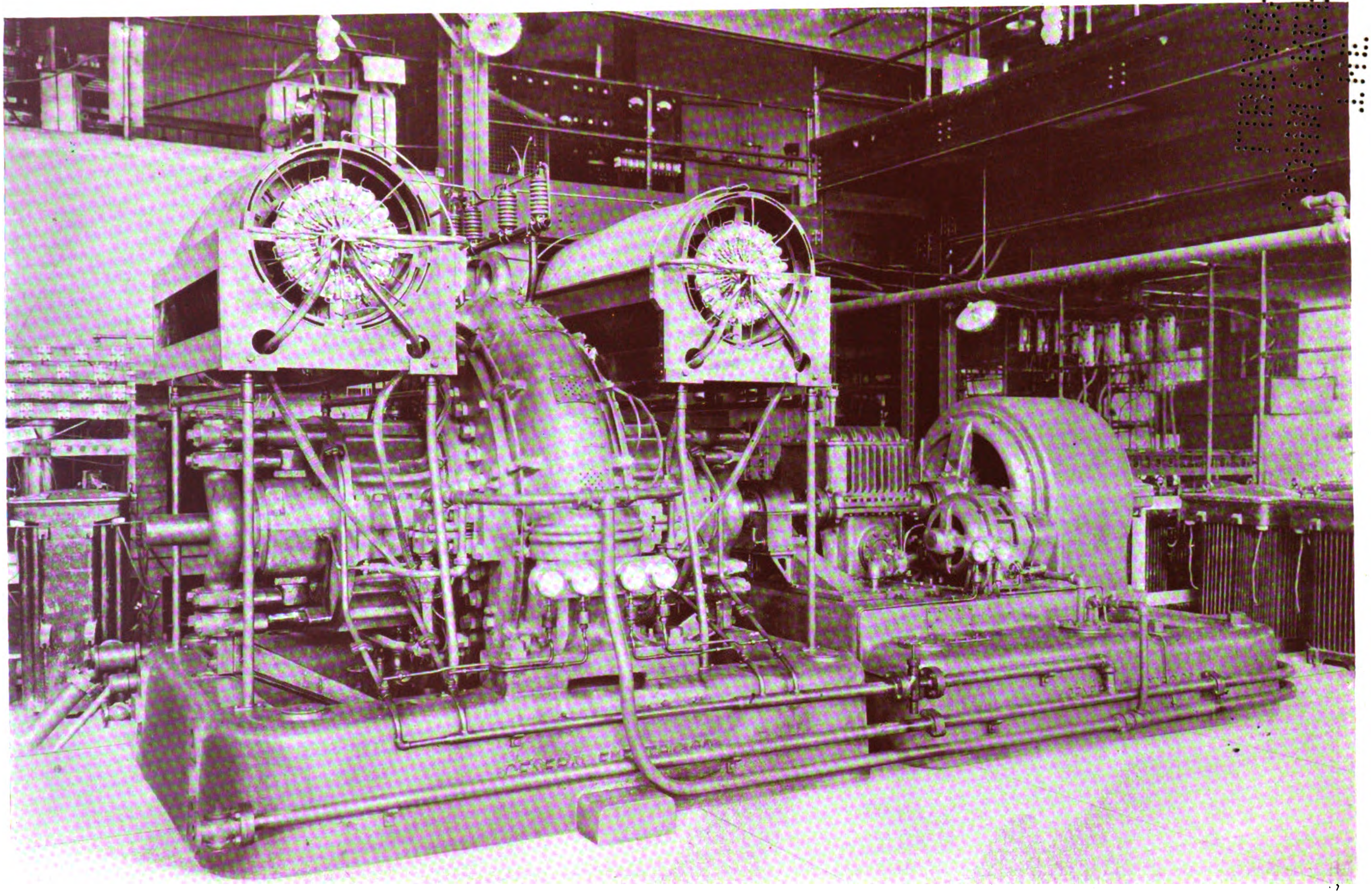


FIG. 1.

200 Kilowatt Alexanderson Radio Frequency Alternator Installed at the Radio Corporation's Transoceanic Station, New Brunswick, N. J. (U. S. A.)

HIGH POWER RADIO APPARATUS FOR SIGNALLING BY CONTINUOUS WAVES—THE ALEXANDERSON SYSTEM FOR RADIO-TELEGRAPH AND RADIO-TELEPHONE TRANSMISSION

By Elmer E. Bucher

GENERAL

Radio engineers early foresaw that the ultimate generator of oscillations for Radio-Telegraphy and Telephony would be one of a type providing more efficient and reliable operation than the systems utilizing the "arc" and "spark." In fact the literature of the past makes frequent references to the desirability of an oscillation generator constructed along the lines of an ordinary power-house alternator; but because such alternators were required to provide frequencies a thousand times or more in excess of those used in power engineering, new problems of designs were encountered which were declared by many to be well-nigh insurmountable. For a time the development of the art seemed to follow the line of least resistance, and it resulted in the evolution of several systems utilizing the "arc," the "spark gap," and the type of radio frequency alternator which generates at a comparatively low frequency, the necessary increase of frequency being obtained either by groups of mono-inductive transformers external to the alternator, or by tuned "reflector" circuits associated with the alternator. None of these systems, however, can be said to have satisfied fully the exacting requirements of commercial operation.

An oscillation generator suitable for commercial radio service over great distances, should possess the following qualifications:

(1) It should generate a steady stream of oscillations of constant amplitude.
(2) It should generate a so-called "pure" wave; that is, a fundamental wave in which the radiation incurred by super-imposed harmonics is negligible.
(3) It should provide a performance as reliable as the ordinary power dynamo.
(4) It should operate economically and efficiently.
(5) It should permit manufacture of units in any desired power.
(6) The design of the whole system should be such as to permit telegraphic signalling at very high speeds.

The above specifications are met fully and fairly in the Alexanderson System.

As is well known, the design of radio frequency alternators has occupied the attention of Mr. Ernst F. W. Alexanderson of the General Electric Company (U. S. A.) and his staff for a number of years, and the pioneer work of these men in that branch of radio research is now a matter of common knowledge. Starting with the development of several experimental types of alternators, they have steadily progressed toward the designs of more powerful machines which are now available for commercial use. Standardized alternator sets for transmission at wave lengths between 6,000 and 10,000 meters and between 10,500 and 25,000 meters, are now in production. This description is devoted principally to the discussion of a 200-kilowatt set, although sets of other powers are now under construction.

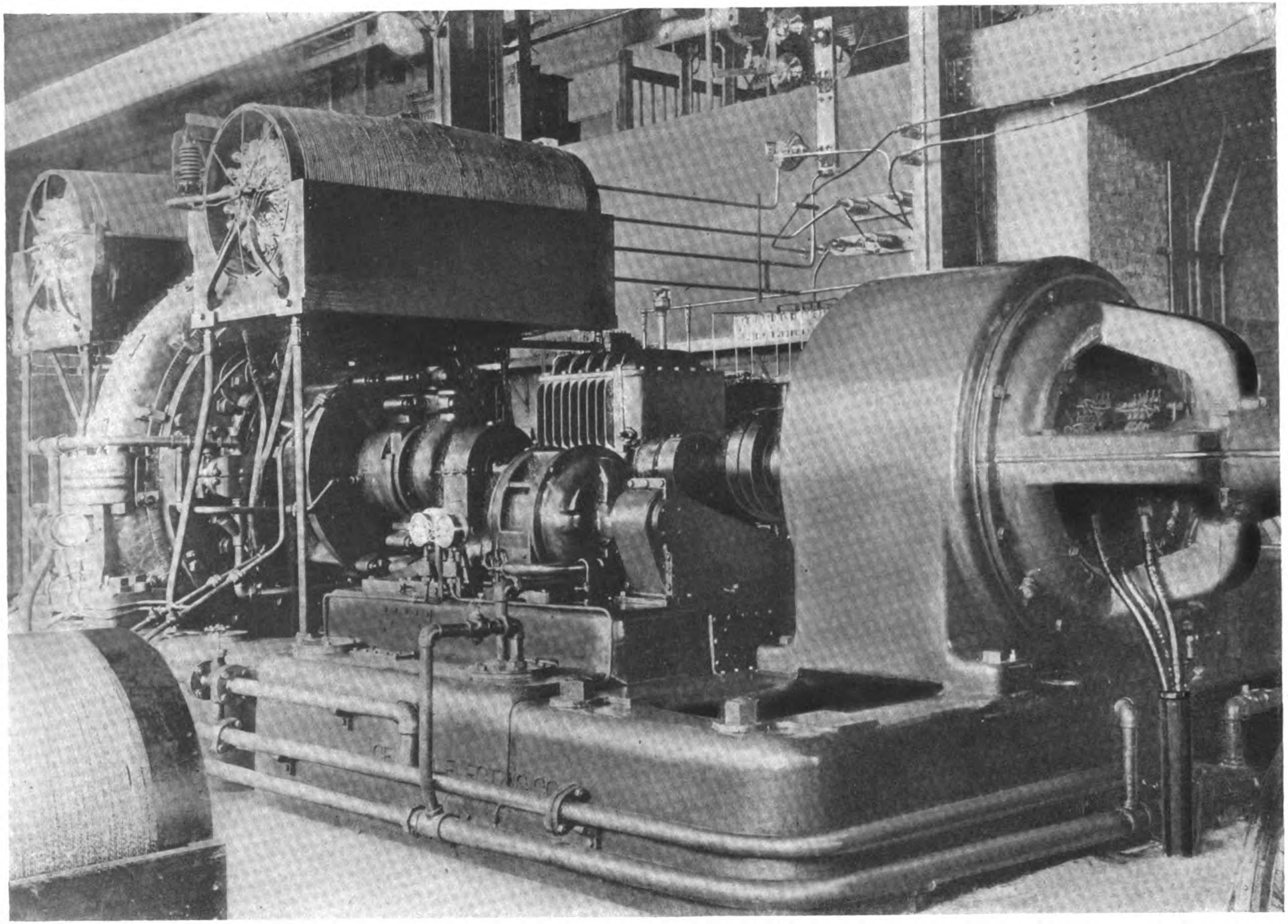


FIG. 2.

Motor End View of 200 Kilowatt Alexanderson Alternator.

The typical Alexanderson high-power station may be said to represent a radical departure from current ideas regarding radio design. In fact, at first glance, it seems to possess little in common with the apparatus of other systems. These features will presently be described in greater detail.

The Radio Corporation, after an extensive test of the Alexanderson System at its high power station at New Brunswick, N. J. (U. S. A.), has acquired the rights to the Alexanderson System, and it will be employed at all its stations devoted to long-distance signalling. A 200-kilowatt alternator set was installed at New Brunswick in September, 1918, and from that time it has provided continuous and most satisfactory service in continent-to-continent communication. Normal transmission is at present conducted at the wave length of 13,600 meters, with antenna current of 400 amperes corresponding to an alternator output of approximately 80 kilowatts. With this fractional value of the available output of the alternator, trans-oceanic communication has been maintained with European stations throughout the twenty-four hours of the day. The alternator is capable of supplying 600 amperes to the New Brunswick antenna, but its full output of 200 kilowatts is not at present utilized, due to the lack of adequate power supply at that point. The alternator, as installed at the New Brunswick station, is shown in Figs. 1 and 2.

With this brief disclosure of progress to date, there will follow an explanation of the basic principles of the Alexanderson System and the fundamental circuits of a typical station. This may be accepted as indicative of a standard 200-kilowatt installation, although largely based upon the apparatus at the New Brunswick station.

STANDARD EQUIPMENT

A high power radio station of the Alexanderson type contains three important developments:

(1) An ALTERNATOR—which generates currents *directly* at the frequencies which are required for the radio circuits with which it is associated. The frequency of these currents is solely dependent upon the number of field poles on the machine, and upon the speed at which the rotating member is driven. This is in distinct contrast to certain other systems in which the radio frequency currents are obtained *indirectly* by means of "reflector circuits" or frequency raising transformers electrically associated with the alternator.

(2) A MAGNETIC AMPLIFIER—which provides a non-arcing control of the alternator output for radio telegraphy, and is equally applicable to radio telephony.

(3) A MULTIPLE TUNED ANTENNA—a development which has markedly reduced the wasteful resistance of the flat-top antenna, and has therefore increased the transmitter overall efficiency many fold.

ALTERNATOR DEVELOPMENT

To date the development in Radio Frequency Alternators has included the following types:

(1) 2-K.W., 100,000 cycle alternators.

(2) 50-K.W., 50,000 cycle alternators.

(3) 200-K.W., 25,000 cycle alternators.

The characteristics of several alternators of other power outputs have been investigated from time to time. A standard 25-K.W. and a 5-K.W. alternator are now under construction and will be shortly put into commercial production.

With the object of providing a distinct range of frequencies, both the 25-K.W. and the 200-K.W. alternators are manufactured with armatures and rotors with different numbers of poles; also with gears of different ratio for different driving motor speeds. Thus the 25-K.W. machine

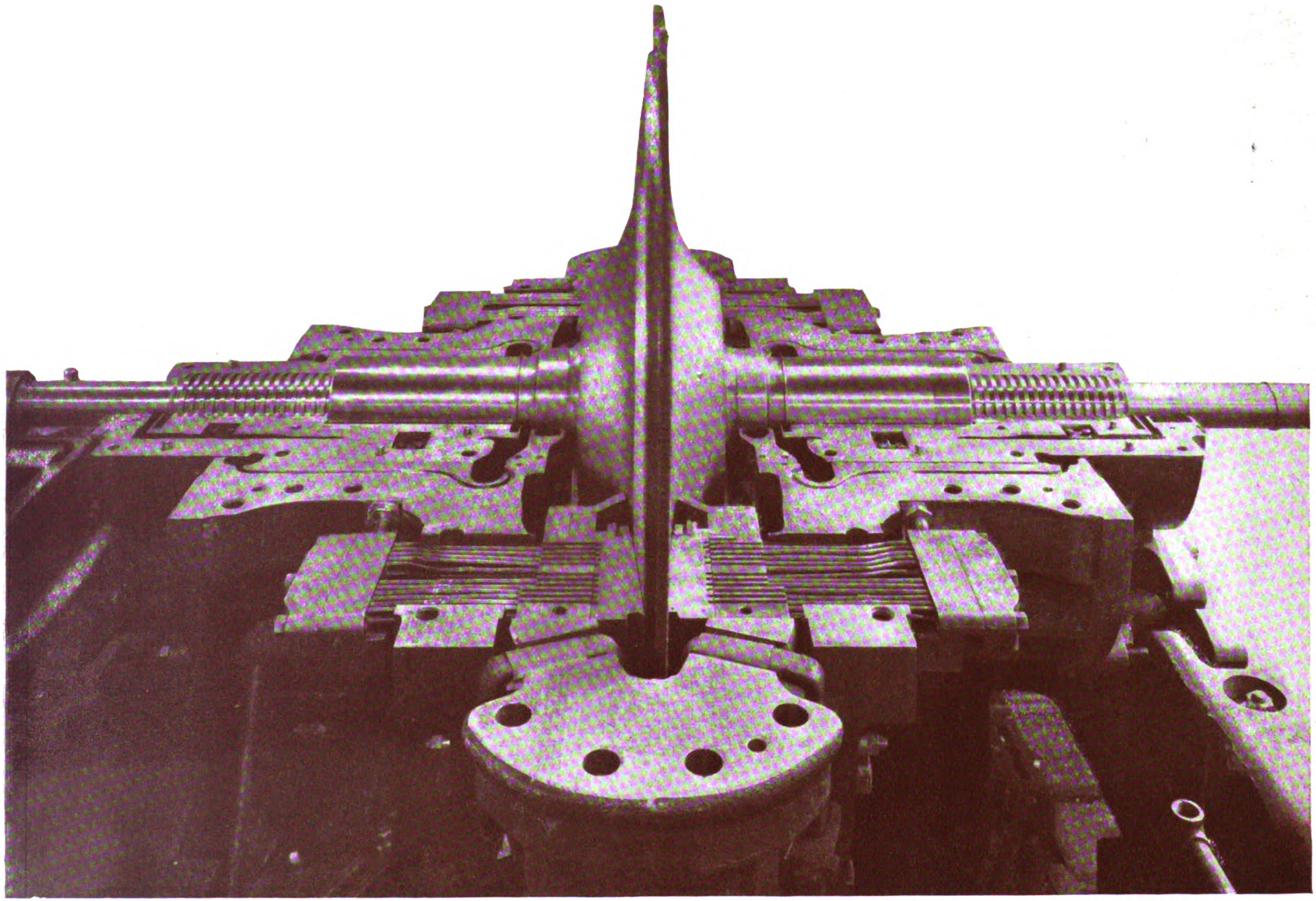


FIG. 3.

200 Kilowatt Alexanderson Alternator, with Top Half Removed.

can be assembled for any wave length from 6,000 to 10,000 meters, and the 200-K.W. machine for any wave length from 10,500 to 25,000 meters. Frequencies lower than these for which the machine has been assembled can be obtained by running the alternator at a reduced speed.

The standard drive for the 200-K.W. Alexanderson alternator is two-phase, 60-cycles, 2,300-volt alternating current. By the use of suitable transformers, the voltage of the power supply can readily be transformed to the value for which the motor was designed. Special driving motors and control equipment can be supplied for frequencies other than 60/50 cycles.

THE ALTERNATOR

The Alexanderson alternator is an *inductor type* of generator with a solid steel rotor having several hundred slots milled radially on each side of the rim. The slots are filled in with non-magnetic material, with the object of reducing wind friction to a minimum. The fillers are brazed into the disc in order that they may withstand the centrifugal strain of rotation. The rotor is designed for maximum mechanical strength by providing it with a thin rim and a much thicker hub. With this construction the strain on the material due to centrifugal force is the same from the shaft to the outer rim.

The *rotor* of the 200-K.W. alternator (with half of the field frame removed) is shown in Fig. 3. This also shows the collars of the thrust bearings and a partial sectional view of the main bearing housings.

An assembled 200-K.W. alternator with its driving motor is shown in Fig. 4. The alternator is driven by a 600-H.P. induction motor of the wound-rotor type, which is operated from a 60-cycle, 2,300 volt, quarter-phase source of supply. The motor is connected to the alternator through a double helical gear (with a speed step-up ratio of 1:2.97), which operates in a container partially filled with oil.

The *main bearings* and the *thrust bearings* of the alternator are oil-lubricated by force feed at pressures varying from 5 to 15 pounds according to the demand on the bearing. During the periods of stopping and starting, and in possible emergencies, oil is supplied by a special *motor-driven pump* mounted on the alternator base. When the alternator is working under normal operating conditions, a *separate pump* geared to the main driving shaft feeds the bearings, and the *motor-driven pump* is automatically cut out of service. The *oil-supply tank* is located in the base of the alternator, to which the oil returns after being pumped through the bearings. The oil gauge on the main feed pipe is fitted with a *signalling circuit* to call the attention of the operator in case the oil supply fails. The main bearings of the alternator, which are self-aligning, are also *water-cooled* by a series of copper pipes which run through the bearings near to the friction surface. The armatures of the alternator are also water-cooled from the same pumping source by a series of parallel copper tubes cemented in the frame alongside the laminations.

In order to avoid large losses through magnetic leakage, the air gap between the rotor and the stator frame is maintained at a spacing of 1 millimeter. It is important that the rotor be kept accurately centered, for otherwise the armature coils on one side of the rotor will become overloaded. This is accomplished by the use of specially designed *thrust bearings* which are inter-connected by a set of *equalizing levers* with an adjustable controlling leaf between them. These prevent the possibility of binding between the thrusts, due to expansion of the shaft from heating, and they also take up automatically all slack in the bearings as they become worn. Any tendency towards a change in the air gap is thus counteracted by the action of the levers. The equalizers are in part, the heavy vertical column shown at the end of the alternator in Fig. 4. Should the air gap on either side tend to get smaller, the pull of the field on that side would cause an excessive strain on the thrust

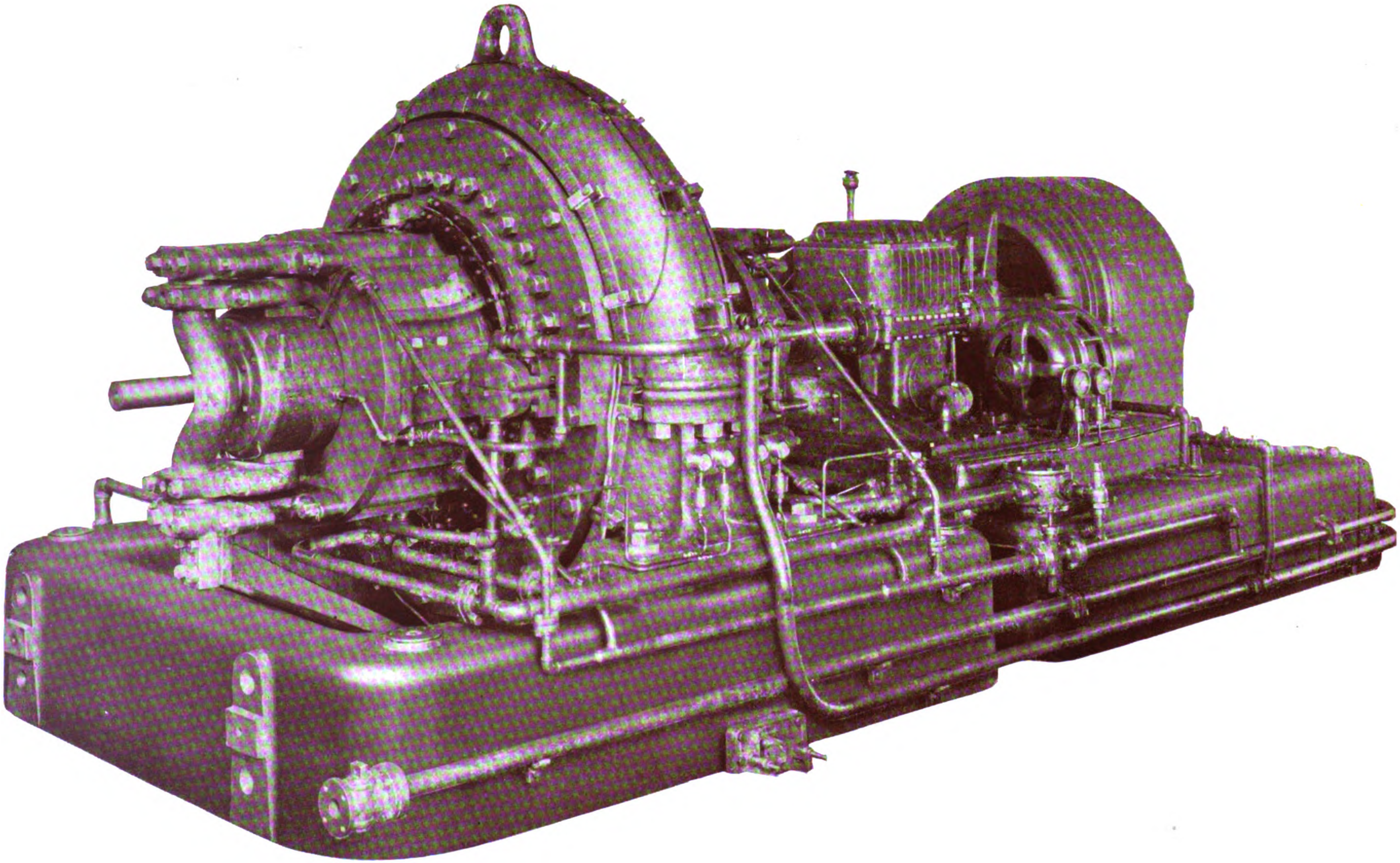


Fig. 4.

200 Kilowatt Alexanderson Alternator, with High Frequency Transformer Removed.

at that end and cause heating. This, however, is prevented by the leverage system, which automatically corrects this and holds the rotor in a central position at all times.

In regard to some of the electrical features of the alternator it will be noted from Fig. 5 that the *armature* and *field coils* are stationary, the requisite flux variations for the generation of radio frequency currents being obtained from the slots cut in the rotor. The diagram points out the fundamental construction of the alternator and the general mode of winding the armature. The rotor disc revolves between the two faces of the field yokes. The direct current supplied to the field coils produces a magnetic field flux which passes between the field yoke faces and through the rotor as shown by the arrows.

The armature coils, which are placed in slots cut in the two faces of the field frames, are shown in the sketch as tipped away from the rotor, although in the actual machine the spacing between the rotor and the frame is but 1 millimeter. Two distinct armature windings are thus provided, one on each side of the rotor. There is but one conductor in each slot and two of these slots make a complete loop, and comprise a *pole* in the armature windings. One slot in the rotor is therefore provided for each loop in the winding. The armature windings on each side of the rotor are divided into thirty-two independent sections, the circuits of which are completed through *transformer primary coils* as shown in Fig. 5. Each primary consists of two turns with sixteen separate wires in each turn. There is no direct connection between the individual armature sections, but, through the two-turn primaries, they combine to act upon the secondary coils of the transformers. It is obvious that with this division of armature circuits the potential on any armature coil (or on the corresponding transformer primary) is very low, and as such, it permits a grounded or open-circuit armature coil to be cut out of the circuit and the operation of the alternator to be continued with but a slight decrease in its output—an obvious advantage.

A detailed view of a portion of the alternator armature windings is given in Fig. 6, and of the preliminary stages of assembly in Fig. 7.

Fig. 8 shows the laminated armature under assembly, which is wound with 0.037 millimeter steel ribbon and afterward machined into the shape of Fig. 9.

The completed rotor and its shaft appears in Fig. 10, while Fig. 11 is an end view of the alternator with the equalizing column removed. Fig. 12 shows the alternator during one stage of the assembly—the driving motor, the alternator transformer and the thrust-bearing equalizing system not having been placed in position.

ALTERNATOR-ANTENNA TRANSFORMER

It is to be noted that a transformer is provided for the armature coils on either side of the rotor. There are therefore two transformers, and they each contain the three coils P_1, S_5, S_1 and P_2, S_5, S_2, shown in the fundamental station diagram Fig. 19. The primary of each transformer contains two turns of sixteen wires each, as mentioned above. The *intermediate coils* S_5 have twelve turns on each transformer. The two intermediate coils are connected in parallel, and are shunted by the magnetic amplifier. The coils S_5 are also connected in series with the secondary proper, and the antenna system.

The *secondary coils*, which consist of seventy-four turns on each transformer, are wound so that their high potential ends are at the center, in order to provide a uniform potential gradient. The two secondaries are connected in parallel and their final terminals are in series with the antenna circuit. More in detail, the low potential terminals of the intermediate coils are connected to the ground, the other terminals of the intermediate coils are connected to the low potential terminals of the secondary coils, and the high potential terminals of the secondary coils to the antenna loading coil. The intermediate coils S_5 are placed between the primary and secondary of each transformer

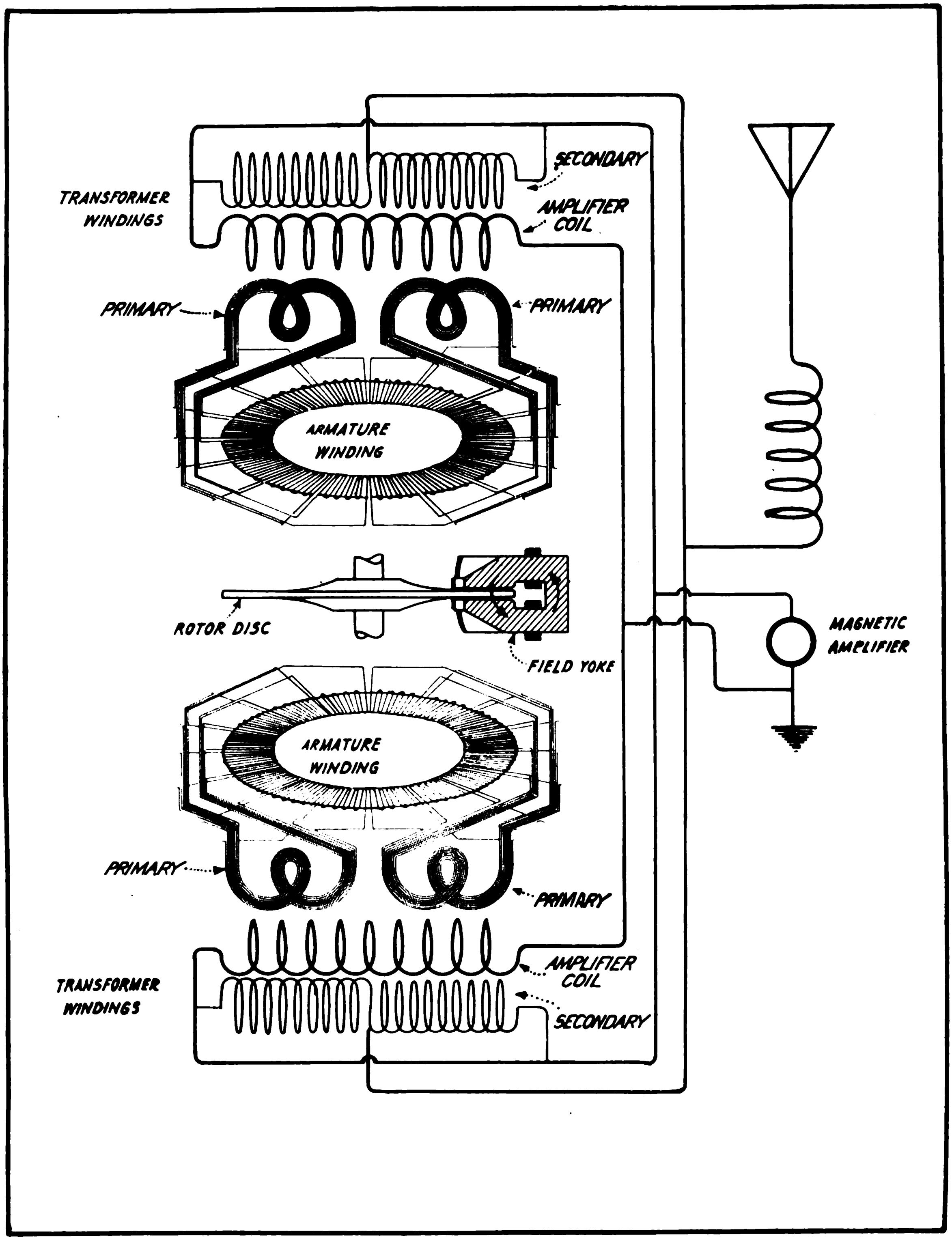


FIG. 5.

Schematic Diagram of Alexanderson Radio Frequency Alternator Circuits.

in order to obtain a close coupling with the alternator. One unit of the high frequency transformer is shown in Fig. 13.

The voltage at the terminals of the secondary winding of the transformer when the alternator is operated at normal speed is about 2,000. The normal output current is 100 amperes. It is thus seen that the alternator is designed for a load resistance of 20 ohms.

SPEED REGULATOR

Since the antenna circuit is directly associated with the alternator circuit, any change in the rotative speed of this machine would throw the alternator circuit out of resonance with the antenna circuit; consequently it is easily seen that the speed variation of a radio frequency alternator for substantially constant output must be held within very close limits. The variable load imposed by telegraphic signalling has a tendency to cause a variation of speed that must be compensated for by some device which operates more critically than any of the mechanical and electrical methods of speed control devised for ordinary power use. The characteristics of any satisfactory governor must be such that a small variation of speed will effect a maximum change in power input to the device under control. To accomplish this, some mechanism must come into such a critical state at the speed to be maintained, that a low percentage of change in speed causes a high percentage of change in itself.

It can be shown that a change in speed of one-quarter of one per cent. from that necessary to maintain resonance will reduce the antenna current in a station utilizing the wave length of New Brunswick—13,600 meters—to one-half its full value. This clearly infers that the speed variation must be much less than one-fourth of one per cent. to maintain a constant output at the alternator. As a matter of fact, a regulation within *one-tenth of one per cent.* is obtained by the Alexanderson speed regulator.

The necessity for close speed regulation becomes equally important when considered from the standpoint of the receiving station. With a modern receiving apparatus of low decrement, a very slight change in the wave length of the incoming signal will materially decrease the received current. A change of wave length or frequency is likewise detrimental when reception is obtained by the heterodyne or beat principle, for should the speed of the alternator vary markedly while signalling, the beat note may vary to the degree that will render it objectionable for ear reception. A variation, for instance, of 50 cycles in the alternator will cause the beat note at the receiver to vary by 50 cycles, which is the equivalent of a speed variation of 0.23 per cent. at the wave length of 13,600 meters.

A solution of the problem of speed regulation with A. C. motor drive was found by Mr. Alexanderson in the use of a *resonance circuit*, which is tuned to a frequency slightly above the frequency to be maintained at the alternator. This circuit is supplied with current from one of the armature coils on the alternator. The current in this circuit increases with alternator speed and, through the agency of a *rectifier*, a D. C. component operates on a *voltage regulator* connected in the circuit of the dynamo which supplies the saturation current for a set of *variable impedances* in the two phases of the motor supply circuit. The function of the regulator is to prevent, within established limits, either an increase or decrease of alternator speed. Additional compensation for the load imposed when signalling is provided by a *relay* which also operates through the D. C. control circuits to vary the line impedances mentioned above. A detailed diagram of the speed control system is shown in Fig. 37, and the theory of operation is disclosed in greater detail on pages 43 to 48.

The panel board of the voltage regulator system is shown in Fig. 14.

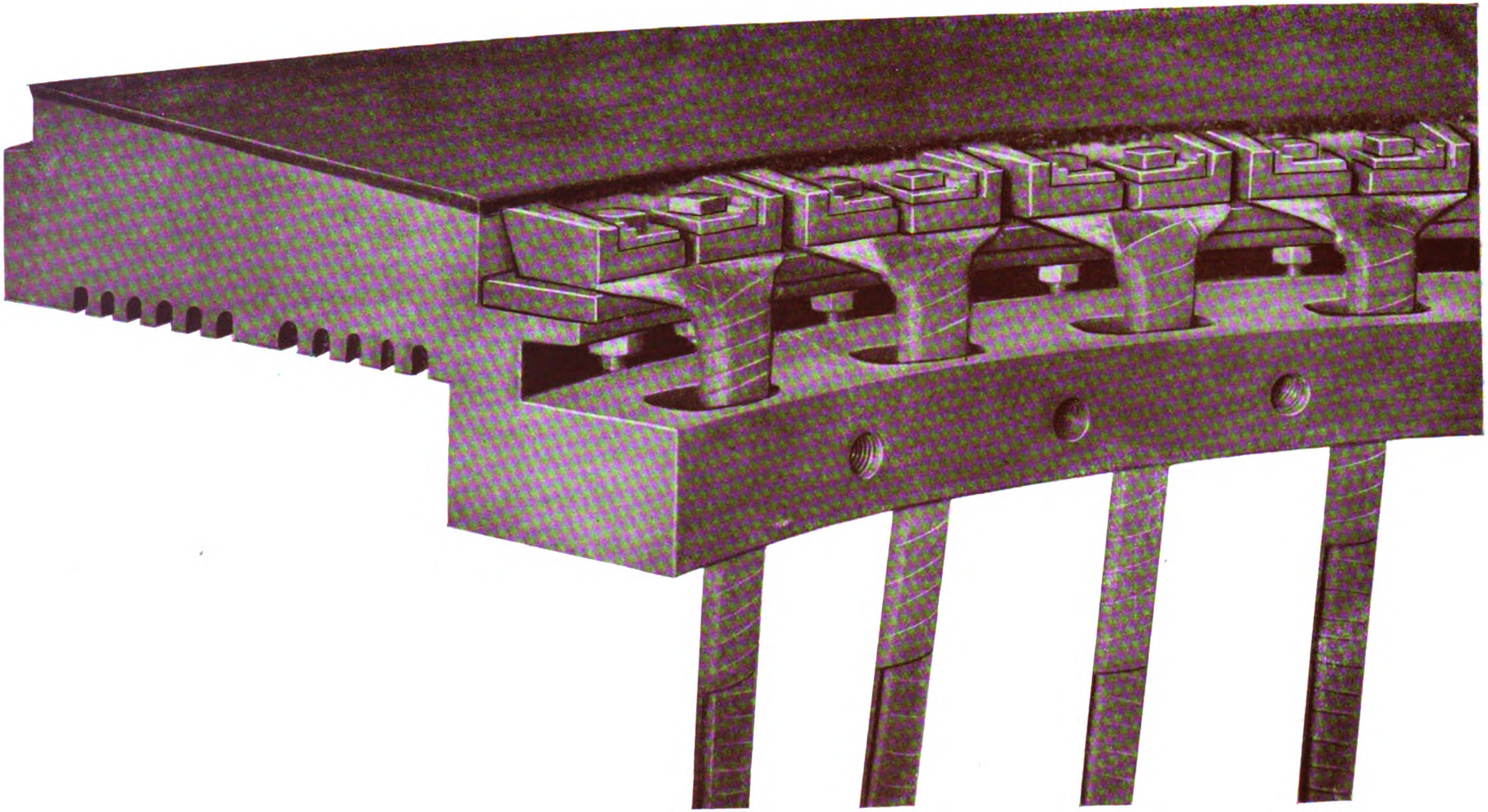


FIG. 6.

Detail View of Section of Armature—Alexanderson 200 Kilowatt Radio Frequency Alternator.

MULTIPLE TUNED ANTENNA

This may be said to establish a radical departure from the types of antennae formerly used for high-power radio transmission. The immediate object of the multiple antenna is to reduce the wasteful resistance of the long, low, flat-top aerials formerly used and to permit the length of such aerials to be increased indefinitely for the use of greater powers. In the case of the New Brunswick antenna, its resistance as a flat-top aerial—3.7 ohms—was reduced by multiple tuning to 0.5 ohm. The radiation qualities of the flat top are not impaired by multiple tuning, as a series of tests have shown that with an equal number of amperes in either type, the *same signal audibility* is obtained at a receiving station, but there is an enormous saving of power in the case of the multiple antenna, as will be presently pointed out.

As shown in the station diagram, Fig. 19, the multiple antenna has, instead of the single ground wire usually employed, a number of ground leads which are brought down from the flat top at equally spaced intervals, and connected to earth through appropriate tuning coils.

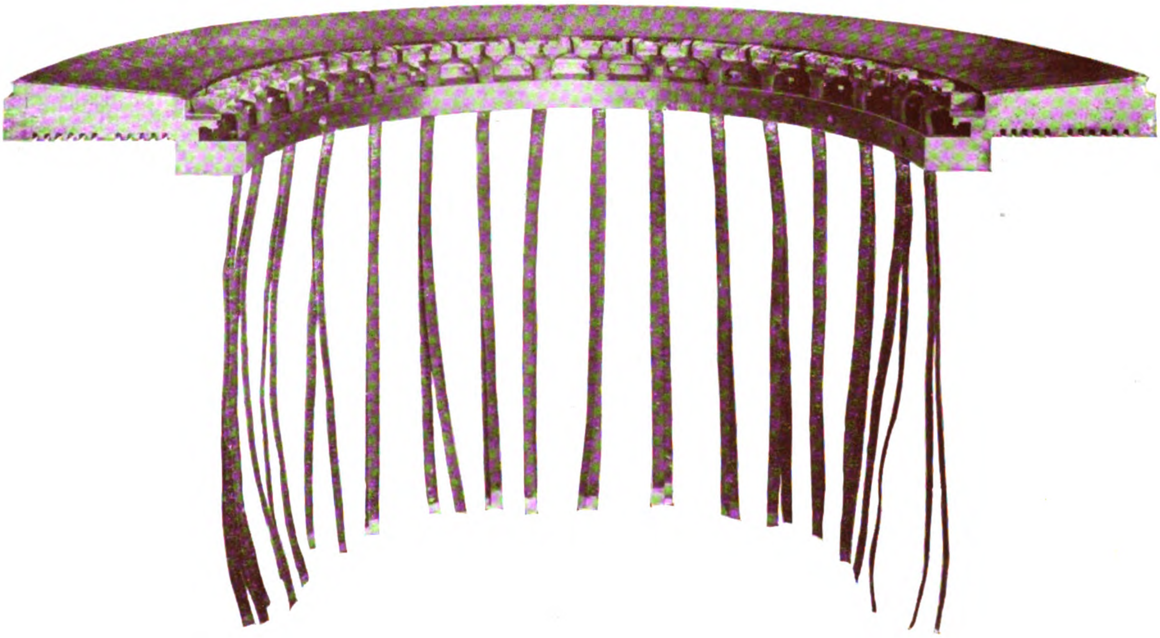


FIG. 9.

A Section of the 200 Kilowatt Alternator Armature.

The capacitive reactance of the flat top is thus neutralized by inductive reactance at six points to earth, instead of but one point as in the ordinary system. The inductive reactance in each down lead is therefore made six times the capacitive reactance at a given frequency. The multiple antenna is thus the equivalent of *six independent radiators*, all in parallel and resonant to the same wave length. Their joint wasteful resistance obviously is much less than that of an antenna with a single ground, and herein lies the saving of power which the Alexanderson antenna brings about.

The relative power imputs required by both types of antennae for the same value of antenna current will be seen from the following illustration: To maintain 600 amperes in the multiple-tuned antenna at New Brunswick, at a resistance of ½ ohm, the power required is $600^2 \times 0.5$, or

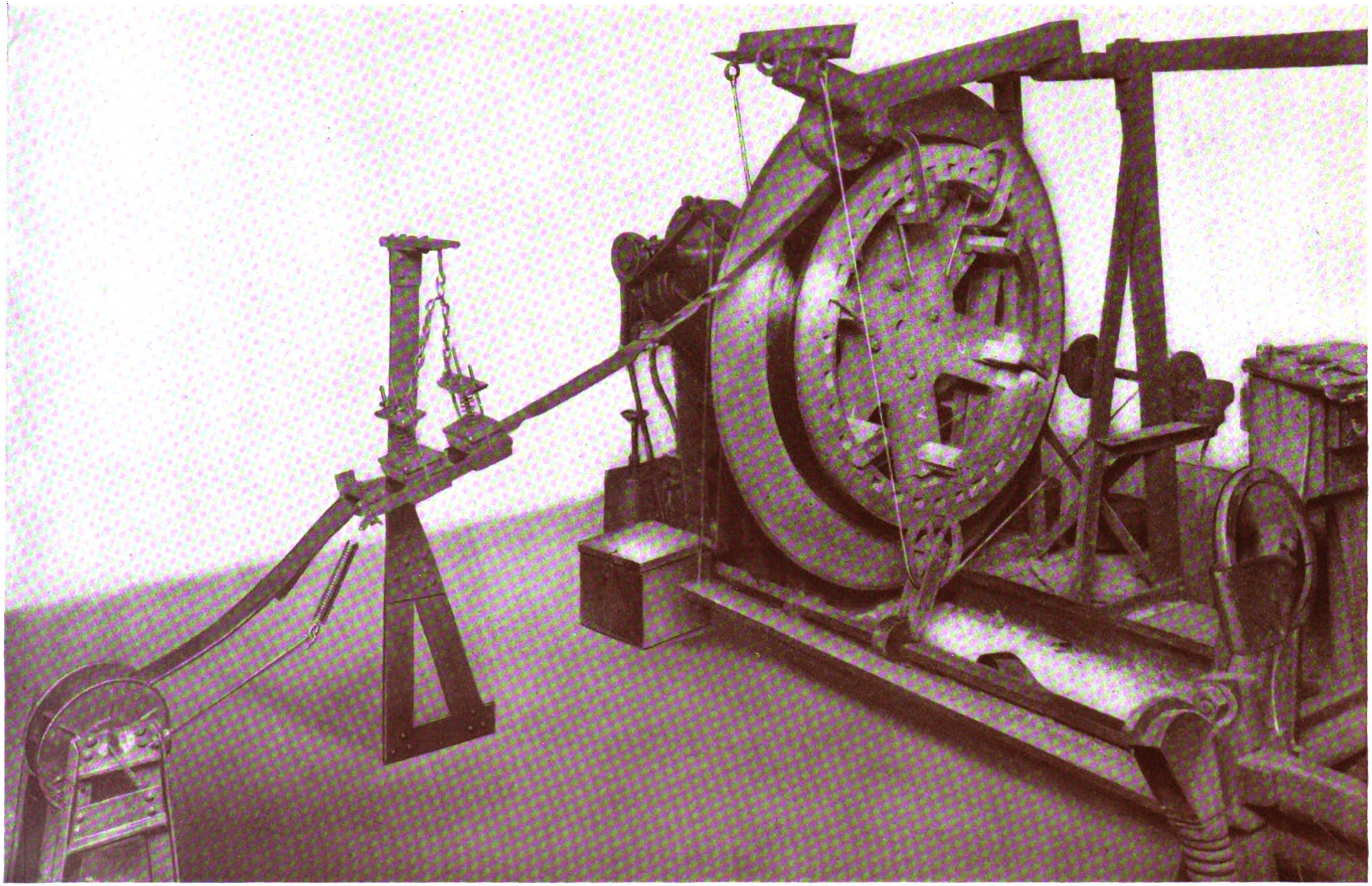


FIG 8.

Showing the Method of Assembling the Armature of the 200 Kilowatt Alexanderson Alternator.

180 K.W. To maintain the same antenna current in a flat-top antenna with resistance of 3.7 ohms requires $600^2 \times 3.7$, or *1330 K.W.* The economy of power secured in the case of the multiple-tuned antenna is an important consideration from the standpoint of the cost of daily operation.

Prior to the advent of the Alexanderson antenna, theory and practice pointed to the desirability of a very high antenna structure for long distance communication at high powers, but as is well known, the cost of erecting an antenna increases very rapidly with the effective height. The multiple-tuned antenna, however, permits the use of a less expensive antenna structure, and gives the same signal audibility at a given receiving station as a high antenna of the old type *with less power*. The example given above demonstrates quite conclusively that the multiple antenna will provide the same antenna current as the flat-top type antenna, but with only one-seventh of the power. The multiple-tuned antenna is treated more comprehensively on pages 29 to 43.

EARTH SYSTEM

The earth-wire system at the New Brunswick station is a combination of a *buried metallic* and a *capacitive ground*. Sixteen parallel copper *conductors* are laid underneath the antenna and buried one foot in the ground. They extend the entire length of the antenna and are space be tween towers somewhat as shown in Fig. 15. A network of wires and zinc plates are also buried in the ground around the station. At each of the five tuning points outside the station, connection is made from the antenna flat top to the sixteen underground wires.

In order to secure equal distribution of current through the buried ground conductors, *equalizing coils* are inserted between the tap on the down lead coil and the earth wires at each of the five tuning points outside the station, as shown in detail, Fig. 15. The function of the equalizing coils is to increase the impedance of the wires near the center and hence force current in the outside wires. Since the coils are wound in opposite directions they add no appreciable inductive reactance to the tuning circuits. In one instance, the use of these coils reduced the multiple resistance of the antenna system from 0.9 to 0.7 ohm.

A still better distribution of the earth currents at New Brunswick was obtained by using a capacitive ground commonly known as a *counterpoise*, which is erected underneath the antenna and a few feet above the earth. A plan view of the counterpoise is shown in Fig. 16. The capacitive ground may be considered as a combination of a tuned and a forced oscillation circuit, and it has the effect of drawing the current from the ground circuit more uniformly than with wires lying on the ground or buried beneath the surface. In practice the total current in the down lead may be distributed between the capacitive ground and the wire ground in any desired ratio. The effect of adding this unit to the system at New Brunswick was to decrease the multiple antenna resistance from 0.7 to 0.5 ohm. The capacitive ground may be divided into separate units for each tuning down lead or the units may be connected together as shown. A schematic diagram of the connections between the flat top and the capacitive and earth-wire grounds is shown in Fig. 16a. The equivalent circuit is given at the right of the drawing. The construction of the *outdoor inductances* for multiple tuning is shown in Fig. 17.

MAGNETIC AMPLIFIER

Telegraphic control of the large antenna currents involved in high-power radio transmitters has ever presented a difficult problem. Particularly has this been true when signalling at high speeds. Rapid signalling obviously requires some device that will not cause destructive arcs and will provide the desired modulation of antenna power without taking upon itself the burden of carrying the full power of the system, during the intervals between signalling.

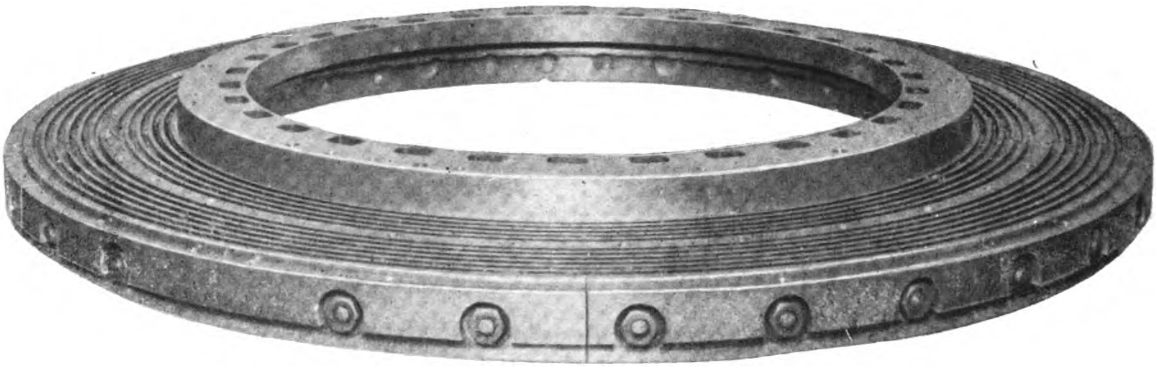


FIG. 9.

Completed Armature Ready for Sawing into Two Sections.

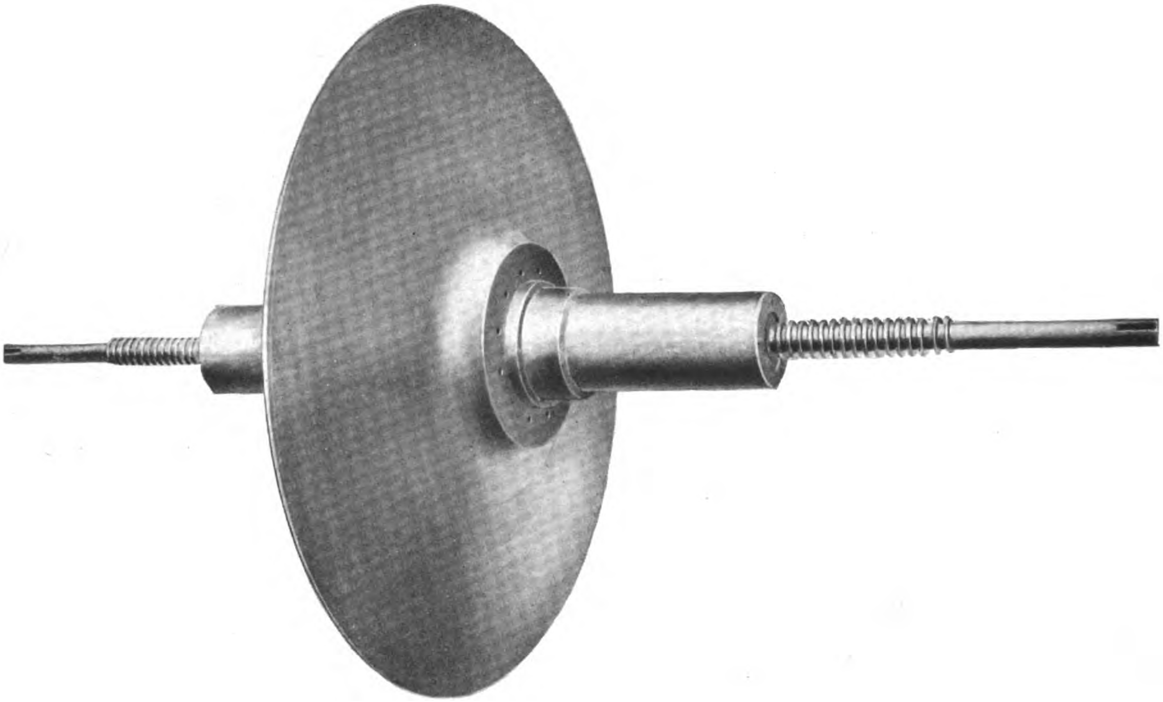


FIG. 10.

Typical Rotor Construction of Alexanderson Alternators.

The *magnetic amplifier* is a device which meets these exacting requirements, for it provides a non-arcing control with a minimum current in the key circuit, and it takes within itself only a small proportion of the total alternator output. A photograph of the amplifier, removed from its container, is shown in Fig. 18.

The magnetic amplifier in general may be described as a *variable impedance* which is connected in shunt with the external circuit of the radio frequency alternator. Its function is to *reduce the voltage* of the alternator and *to detune* the antenna system when the sending key proper is open, and to perform the opposite functions when it is closed. Thus when the sending key is open the amplifier short-circuits the alternator and detunes the antenna system, thereby reducing the antenna current to a negligible figure. When it is closed the output of the alternator is fed to the antenna system.

A general idea of the operation of the amplifier can be obtained from the fundamental circuit, Fig. 19, where it will be noted that the radio frequency coils A and a control coil B are mounted on a common iron structure, and are so disposed that the effect of the control coil upon the radio frequency coils is obtained solely through the agency of flux variations within the core. The impedance of the amplifier is dependent upon the degree to which the iron core is saturated by the control winding. The saturation in turn varies as the current fed into the control circuit. When the control circuit is closed the alternator is short circuited; when it is open, the alternator assumes normal voltage and its output flows into the antenna system.

The magnetic amplifier has been employed in experimental telegraphic signalling at speeds above *500 words* per minute, at which rates it functions without lag. It is equally applicable as a *modulator* of antenna power in *radio telephony*, in which case the control current of the amplifier is modulated at speech frequencies by a bank of Pliotron (vacuum valve) amplifiers, which in turn are controlled by an ordinary speech microphone.

The characteristics of the amplifier are treated in greater detail on pages 48 to 53.

FUNDAMENTAL STATION CIRCUIT

The fundamental *circuits of a typical Alexanderson alternator station* are shown in Fig. 19. Beginning at the left of the drawing, it is to be noted that a source of two-phase, 60-cycle alternating current drives an *induction motor* M, having a wound rotor, the circuits of which include a liquid rheostat R_3. The motor is connected to the *radio frequency alternator* through a helical step-up gear.

The alternator armature coils are indicated at A_3, A_4, the field coils at F_1, and the rotor at A_2. There are two sets of armature coils one on each side of the rotor, which as already mentioned, are divided into 32 sections on each side. The windings on each side connect to the primaries of two transformers shown at P_1, P_2. The primary of each transformer (see Fig. 5) contains two complete turns of 16 wires in each turn, which carry the current developed in the 32 sections of the armature coils on each side of the rotor. As can be seen from the diagram, there is no direct electrical connection between the armature circuits leading to the transformer primary, but the individual primary circuits are disposed so that their magnetic fields at any instant are in the same direction, that is, their fields combine to operate on the secondaries S_1, S_2. In addition to the primary and secondary coils, the two transformers have intermediate coils S_5 which are connected in parallel and shunted by the magnetic amplifier coils A. The coils S_5 are connected in series with the antenna system, and are also closely coupled to the primary and secondary.

The *multiple tuned antenna*, shown in the upper right hand part of Fig. 19, is a long, low, hori-

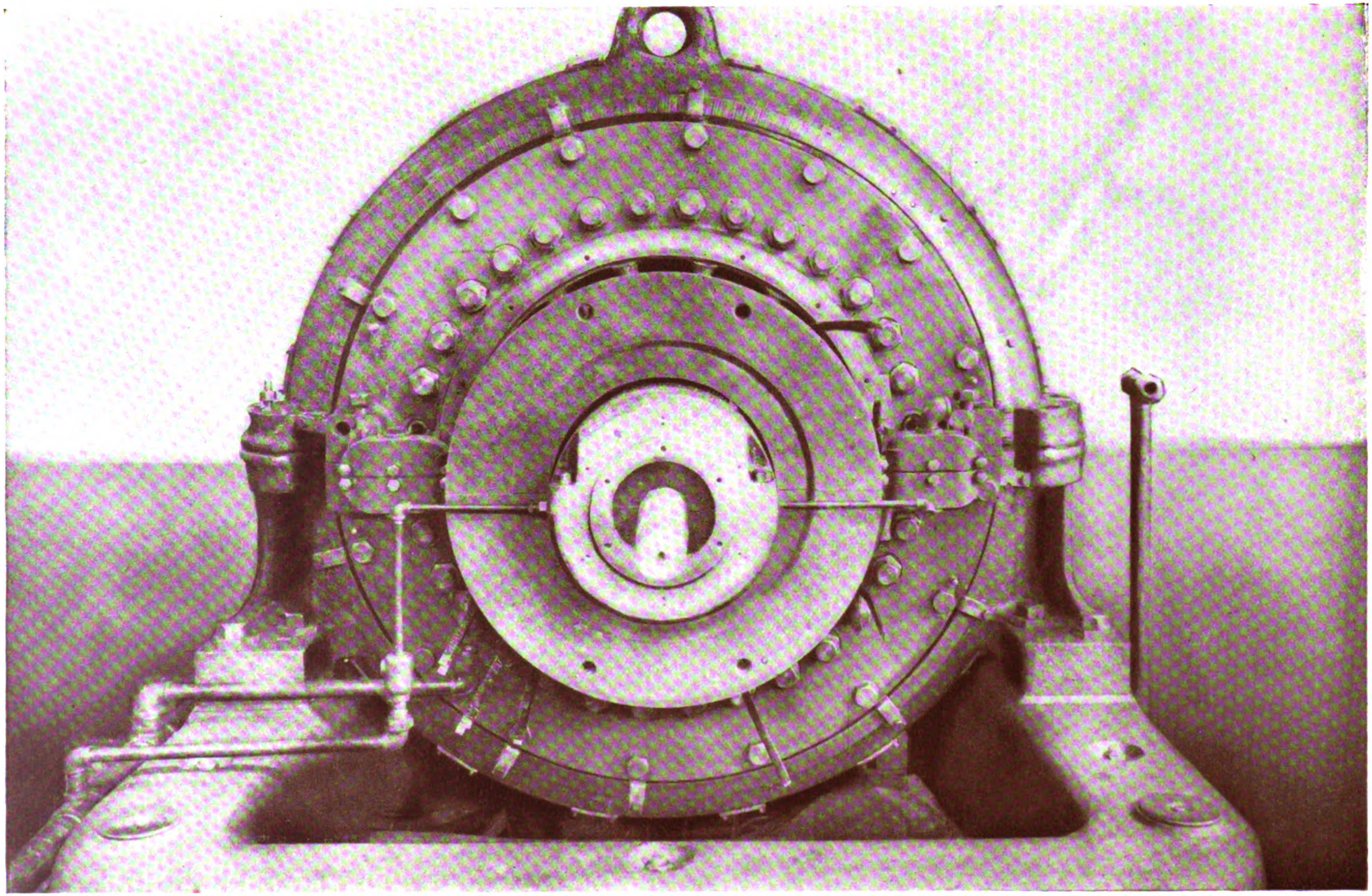


FIG. 11.

End View of 200 Kilowatt Alternator with Air-gap Equalizing Mechanism Removed.

zontal aerial of the Marconi type, from which are brought down leads to earth, which include the tuning inductances L_1, L_2, L_3, L_4, L_5, L_6. For any given wave length the *joint inductive reactance* of the down lead circuits $L_1 \ldots L_6$ is made *equal to the capacitive reactance of the entire flat top* at the operating frequency or wave length. The multiple antenna is therefore the equivalent of *six independent radiating systems* resonant to the same wave length, and for all practical purposes, the oscillating currents in them flow in phase.

The magnetic amplifier, shown to the right of the diagram, comprises the parallel-connected *impedance coils* A, which are connected in series with the *condenser* C_1 and the transformer *amplifier* coils S_5. B is the *control* coil, wound to include both branches of the windings A, which is fed with direct current, regulated by the rheostat R_6. When the control circuit is closed the impedance of the amplifier coils A become a minimum; when it is open the impedance is a maximum. In the former case the alternator is placed on short circuit and the antenna is detuned; in the latter case the alternator assumes normal voltage and its output flows into the antenna system. In practice the capacity of C_1 is selected to neutralize the inductance of windings A for some value of current in the control coil.

The circuits of the *speed regulator* appear in the lower left hand part of the drawing. Note is to be made first of the variable impedances N and O in the motor supply line with their D. C. control coils P_6 and the variable impedance coils S_7.

The extremely close speed regulation essential to alternator operation is obtained from the *resonance circuit* L_{10}, C_4, P_5, the coil L_{10} being one of the alternator armature coils. This circuit is made resonant to a frequency slightly above the normal frequency at which the alternator is to be operated and the current developed therein acts inductively on the circuit S_6, E, M_1—E being a rectifier. The latter rectifies the radio frequency current and sends a D. C. component through M_1, which acts with an increase of speed to decrease the voltage held by the *voltage regulator* M_2 T_1 on the generator K_1. This increases the impedance of the coils S_7 and therefore tends to reduce the speed of the driving motor. As the speed now falls the current in the resonant circuit falls off and likewise that in the coil M_1. This permits the voltage held by the voltage regulator to increase, and therefore acts to reduce the motor supply line impedance and thus increase the speed. A given *mean voltage* is thus maintained in the control circuit by generator K_1, which depends upon the magnitude of the control current in M_1. This keeps the speed variation within exceedingly close limits.

Additional compensation for the load imposed by signalling is obtained by the *relay* T_2, which shunts the resistance R_2 when the sending key is closed. This decreases the impedance of N and O and increases the input to the motor by an amount equal to that imposed by the load, without change of speed. It therefore lightens the duty of the speed regulator proper, making it responsible only for slight irregularities in the power supply or for variations occasioned by the compensating device. The same speed regulation can be obtained at other alternator frequencies by tuning the *resonance circuit* to a suitable frequency.

FUTURE DEVELOPMENT

In event that a larger output than that provided by a single alternator, of 200 K.W. is desired, *parallel operation* is contemplated. Such operation is entirely practicable and will be employed in the Radio Corporation's high-power stations, when great distances are to be covered.

If the dimensions of the multiple antenna are chosen so that the phase displacement of the travelling wave between the different radiators is appreciable, it is possible to obtain *directive radiation*. In fact, it is believed that a variety of polar curves of radiation may be created *by proper*

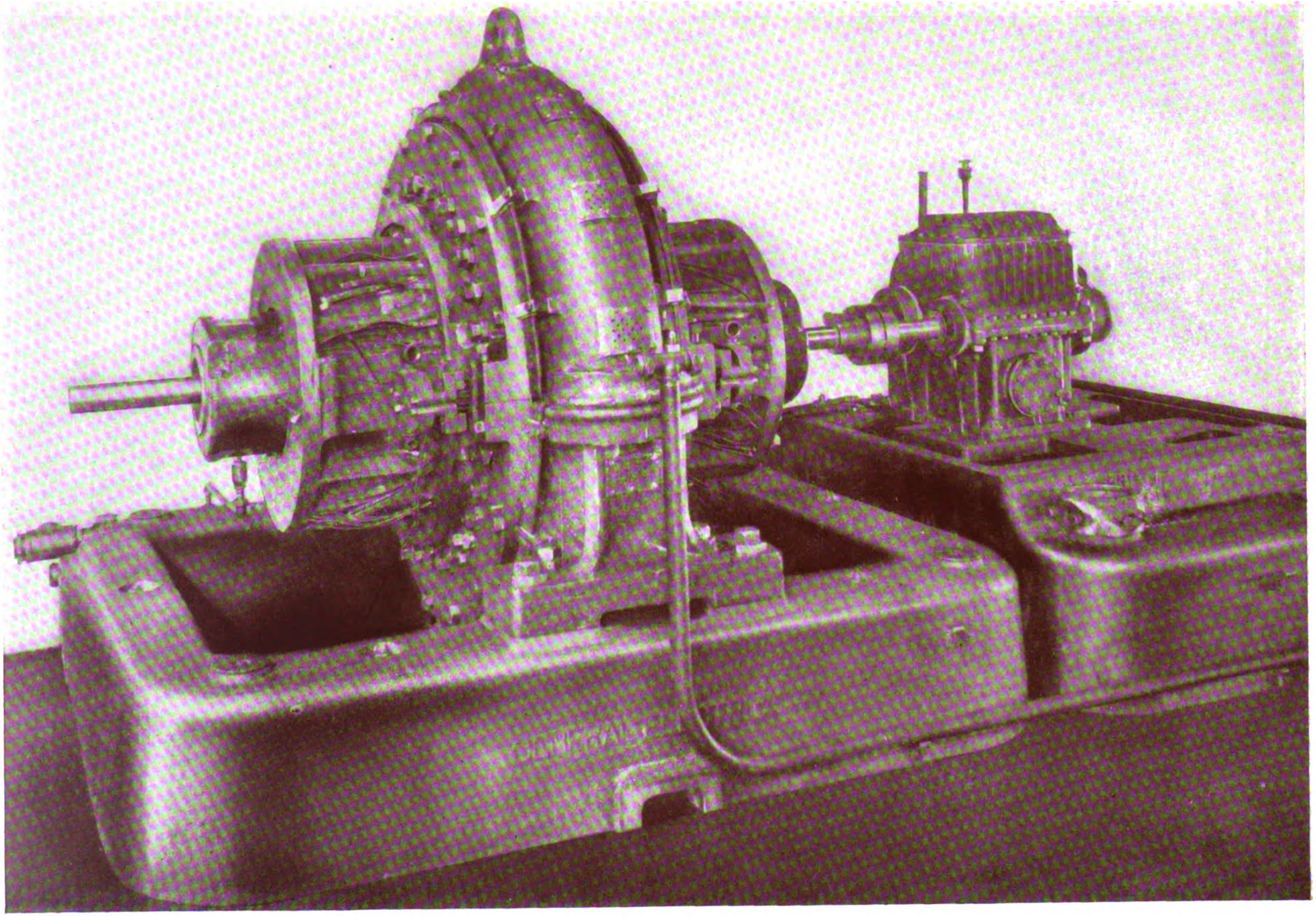


FIG. 12.

200 Kilowatt Alexanderson Alternator Partially Assembled.

phasing o separate sections of the antenna. An analysis of these possibilities shows that efficient and uni-directional radiation should be possible. The multiple antenna makes possible the use of radiators having the physical dimensions of a wave length or more and therefore the directive characteristics outlined above will undoubtedly be realized in practice.

ANTENNA SUPPORT

A standard tower for high-power stations is shown in Fig. 20. This is of the self-supporting type erected on a suitable concrete base. The antenna wires are suspended from the steel cross arm at the top. This method of antenna suspension lends itself admirably to the long narrow antenna which has been found most suitable for the Alexanderson System.

The antenna layout for a two-alternator unit high-power station using these towers is shown in Fig. 21 where two antenna wings of any desired length extend in opposite directions from the station house which is located at the center. With this construction the wings may be tuned to different wave lengths and each energized by a single alternator, thus permitting simultaneous transmission at two different wave lengths; or the two alternators may be joined in parallel to energize both wings at some selected wave length.

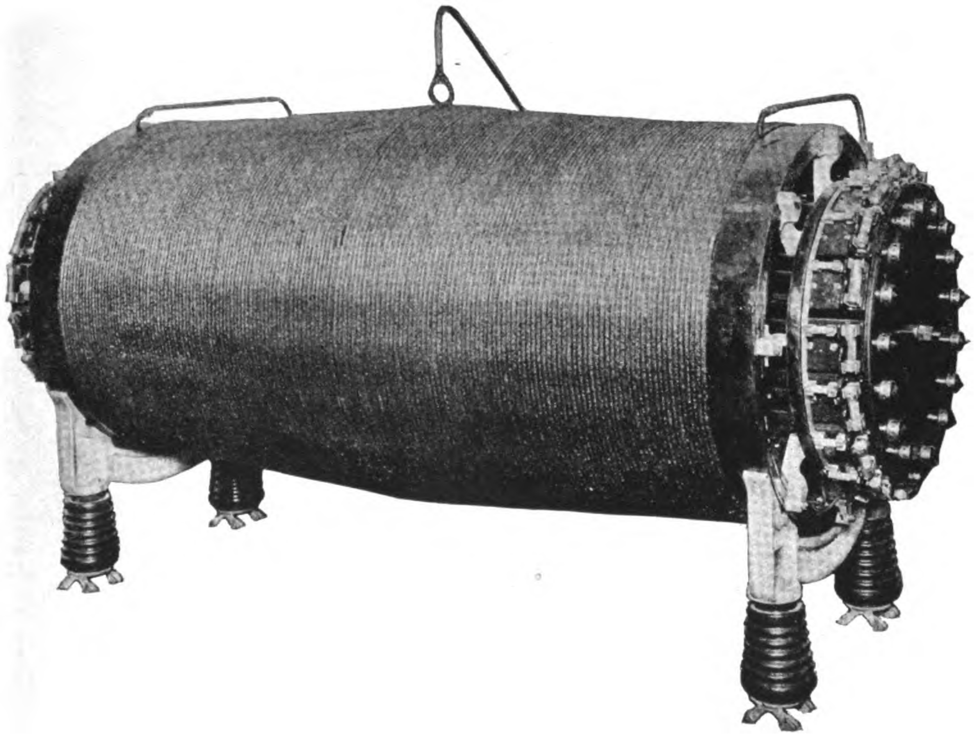


FIG. 13.

High Frequency Transformer.

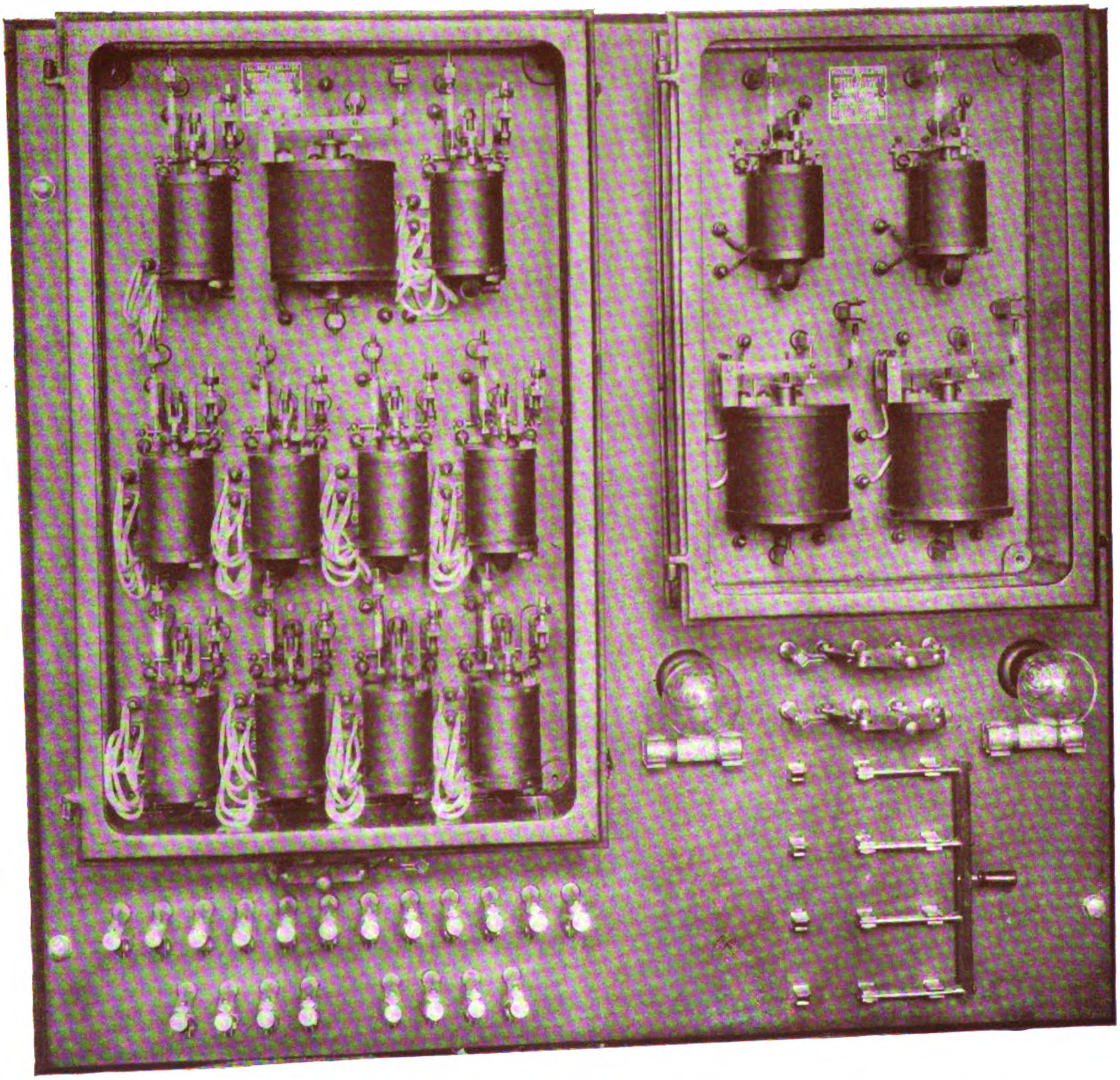


FIG. 14.

Control Panel of Current and Voltage Regulator.

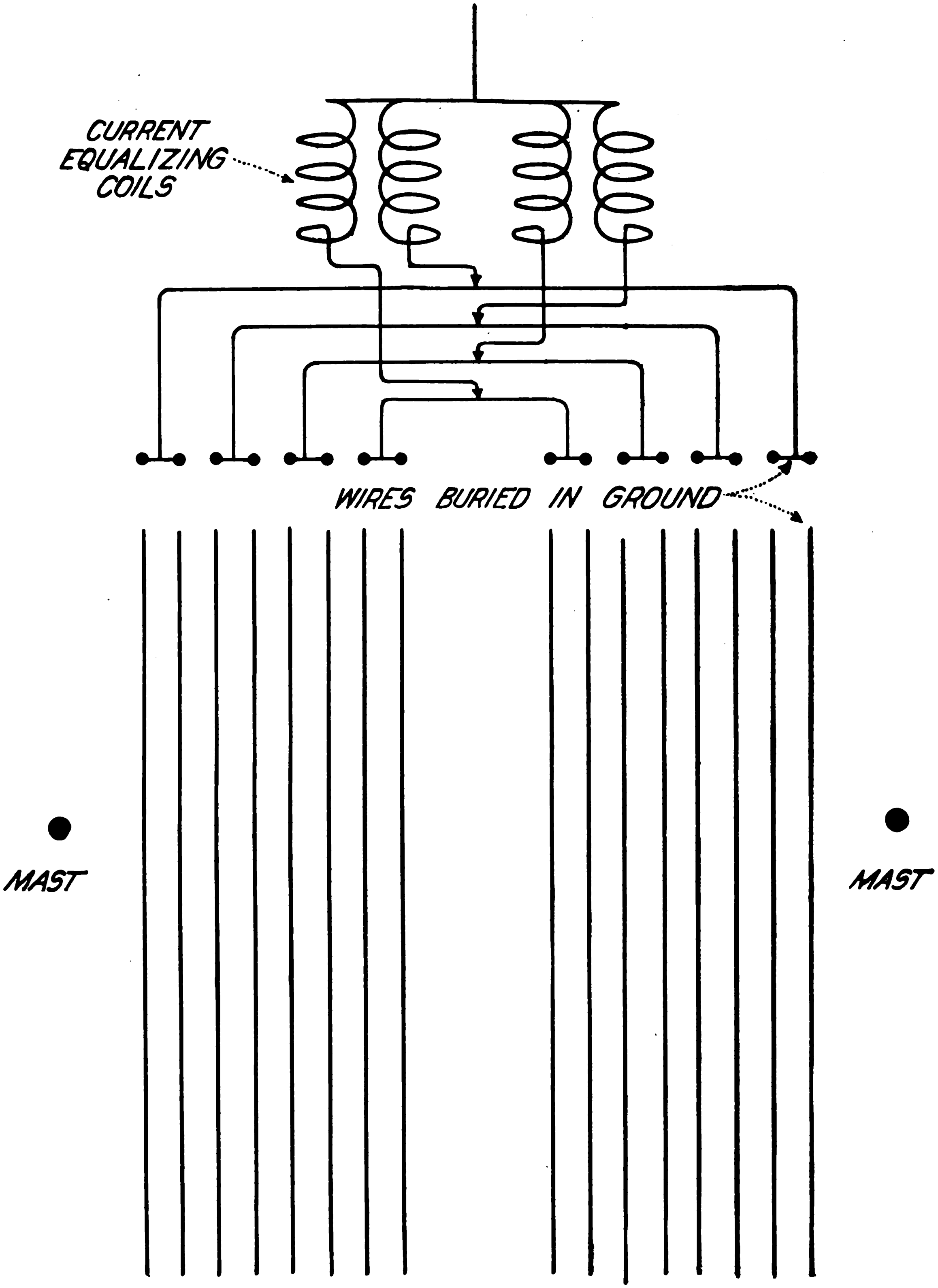


FIG. 15.

Schematic Diagram of Earth-Wire System at the New Brunswick Station.

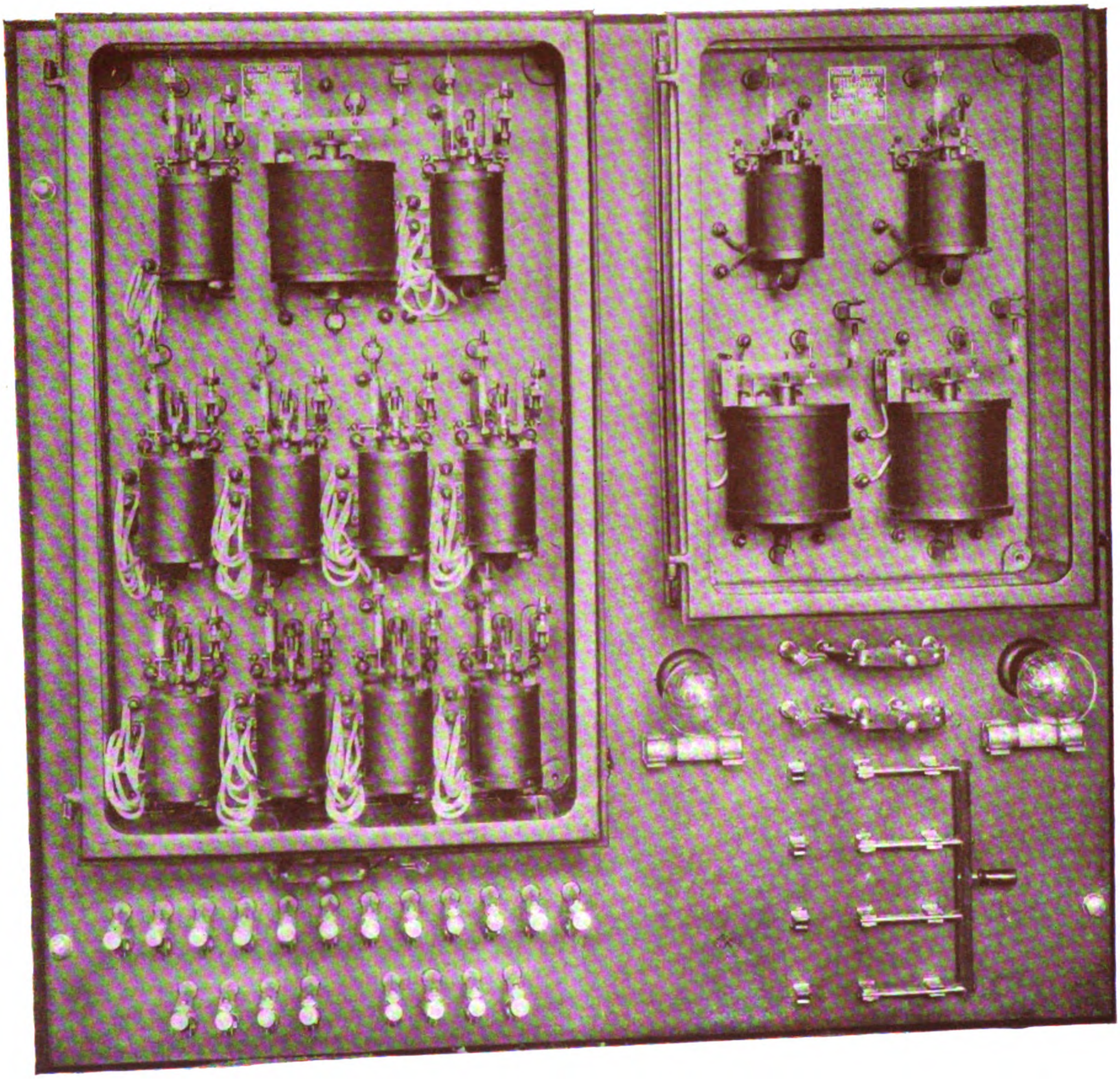


FIG. 14.

Control Panel of Current and Voltage Regulator.

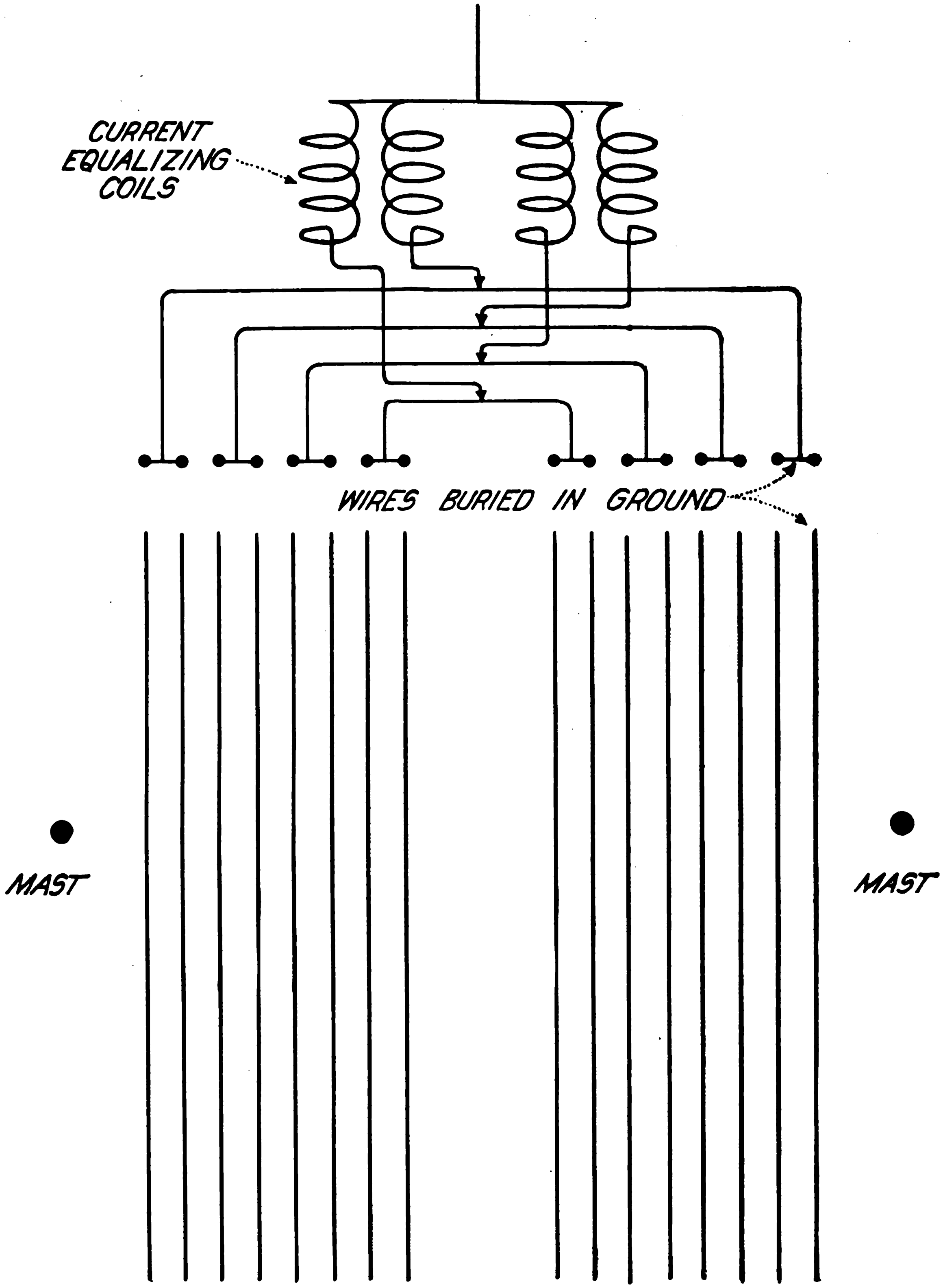


FIG. 15.

Schematic Diagram of Earth-Wire System at the New Brunswick Station,

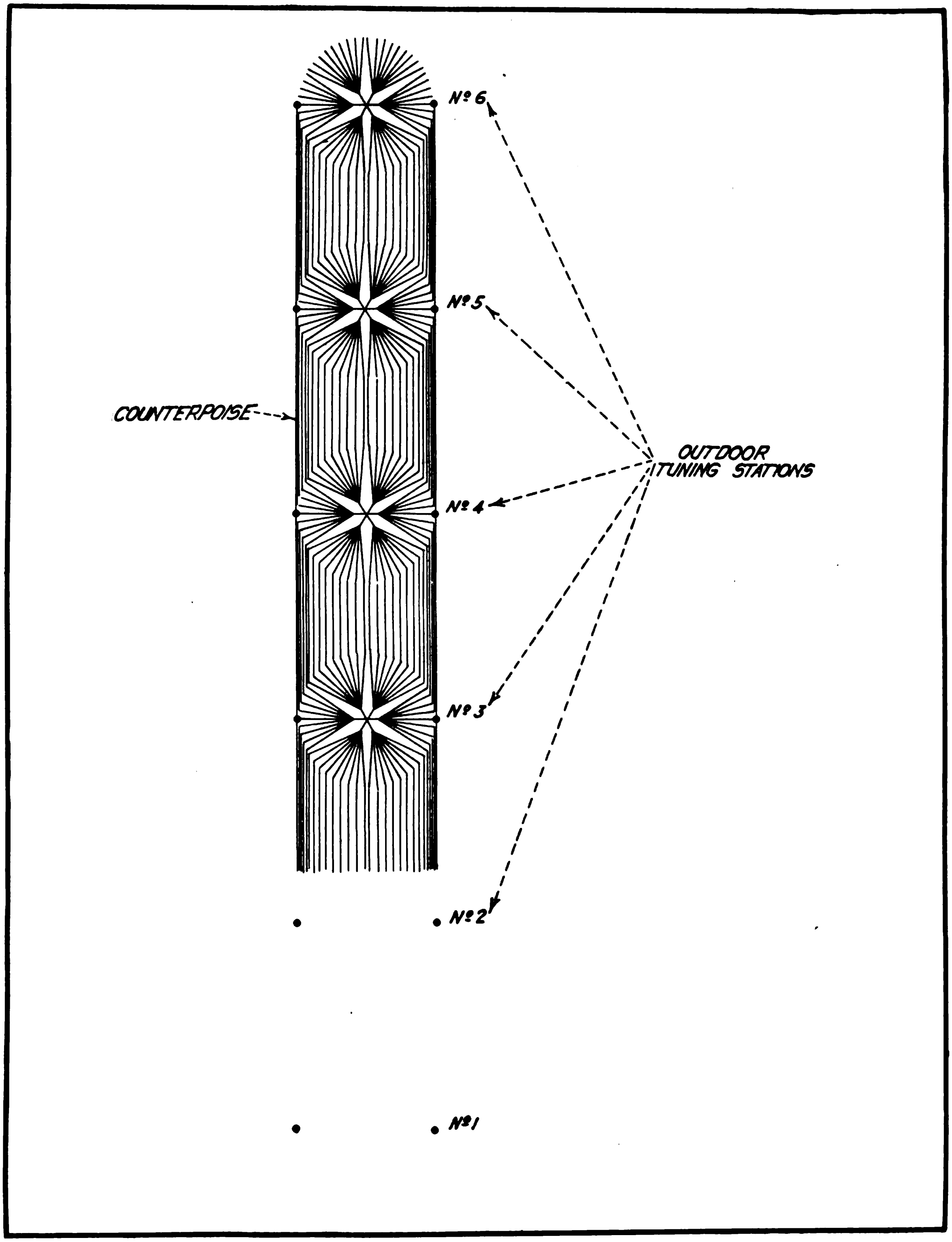


FIG. 16.

Plan View of Counterpoise at New Brunswick Station.

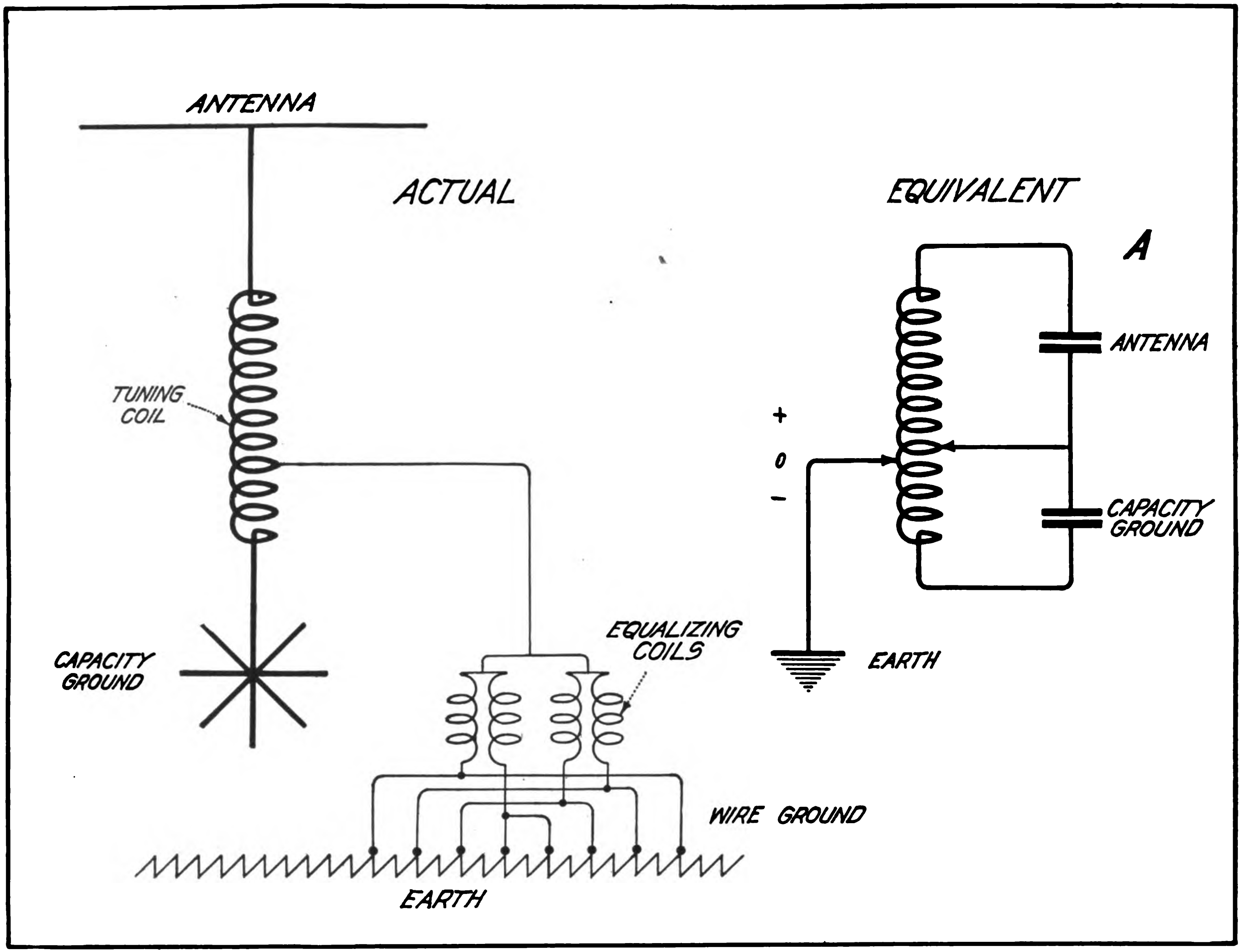


FIG. 16A.

Schematic Diagram of Antenna to Earth Connections of the Multiple Tuned Antenna.

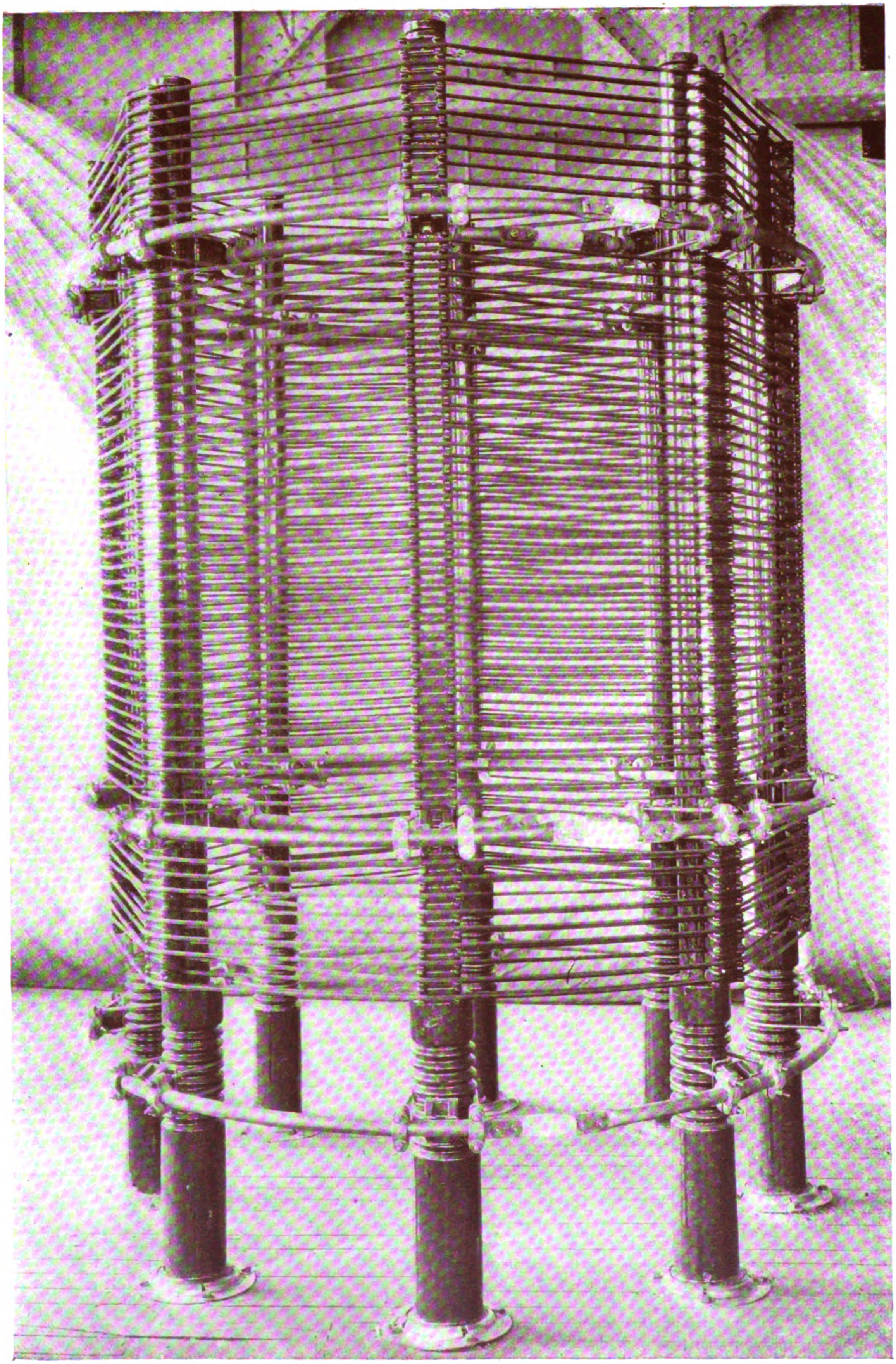


FIG. 17.

Tuning Inductance for Multiple Tuned Antenna

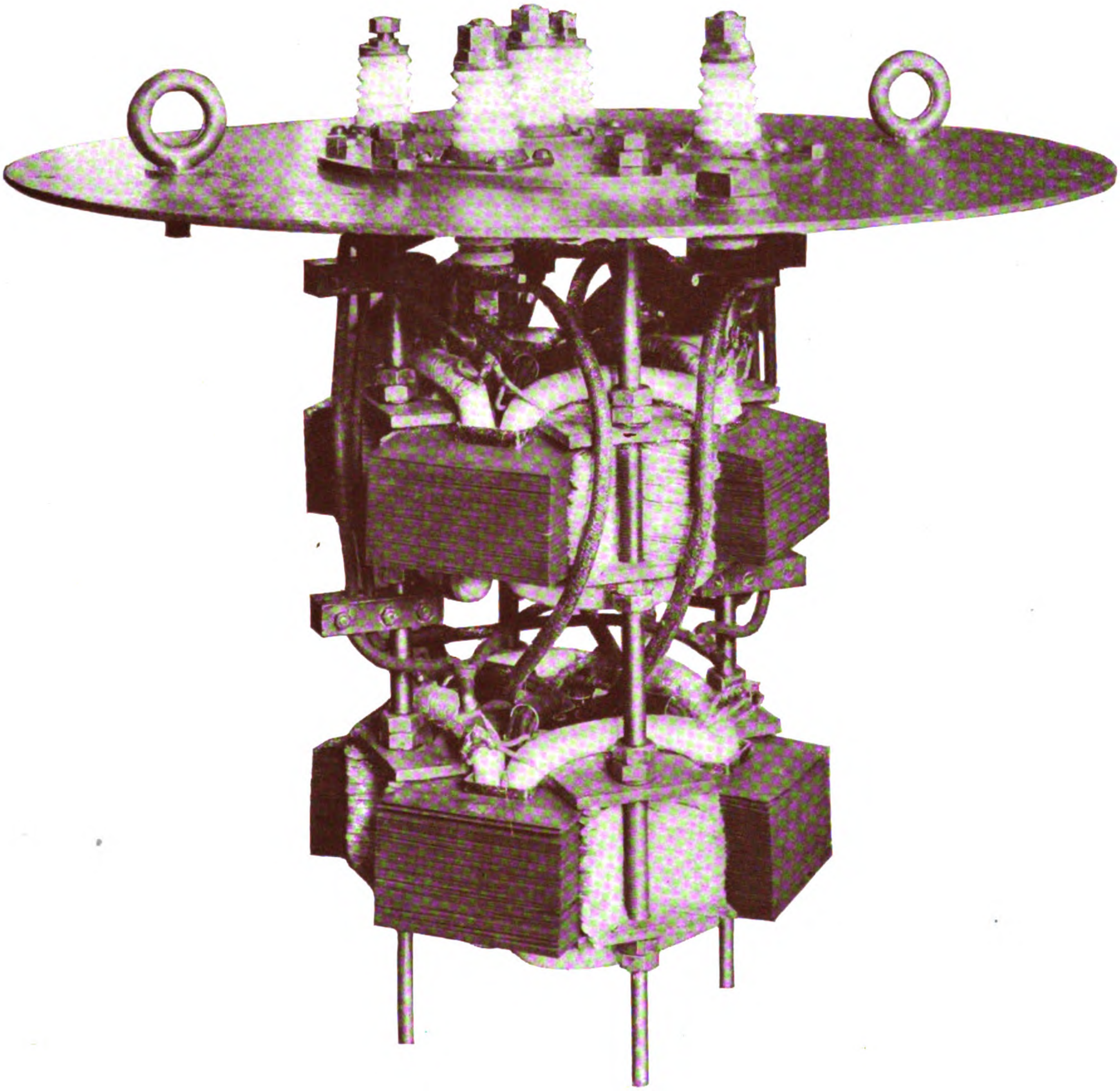


FIG. 18.
Magnetic Amplifier Removed from Containing Case.

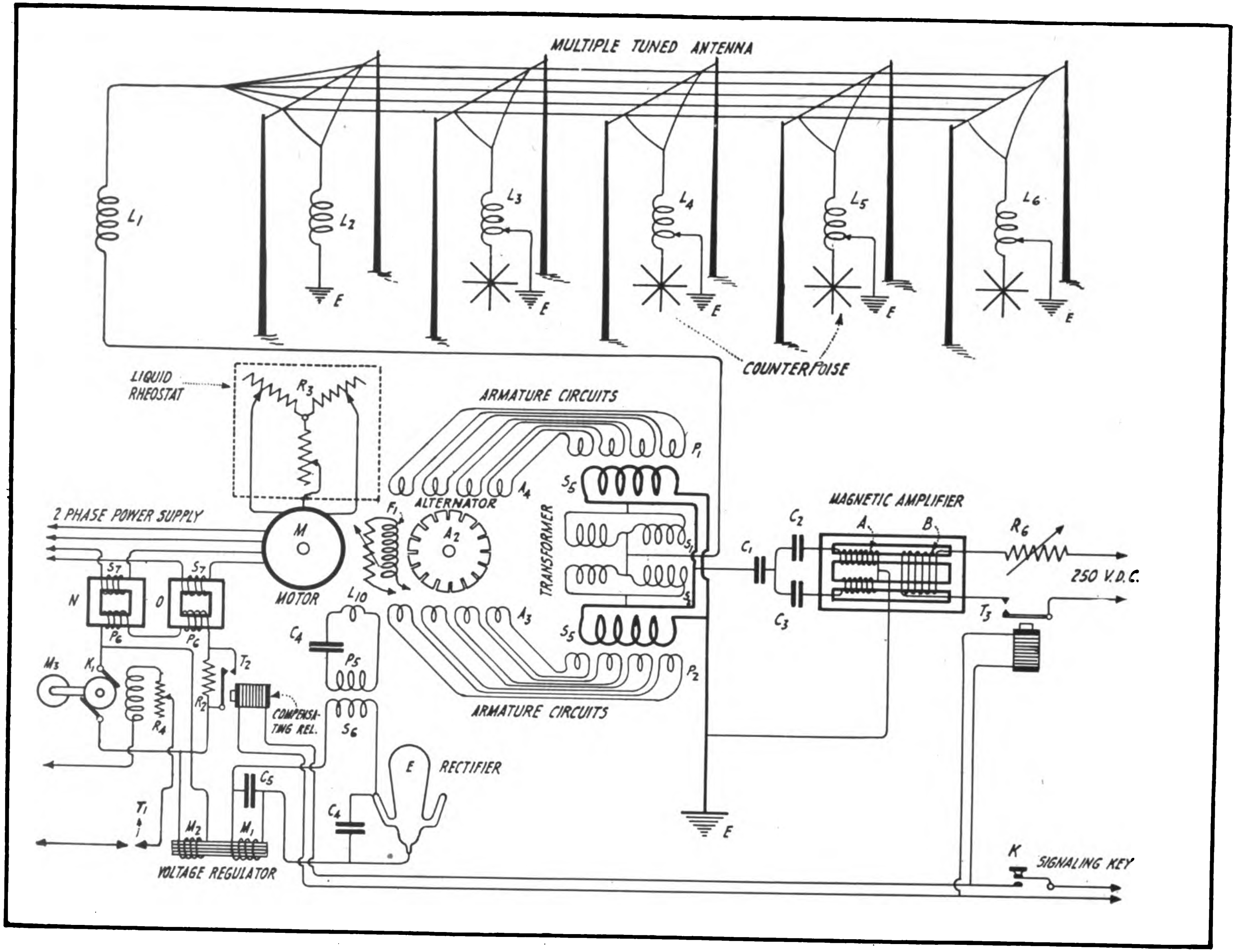


FIG. 19.
Fundamental Station Diagram of 200 Kilowatt Alexanderson Alternator Set, Radio Corporation's Transoceanic Station, New Brunswick, N. J. (U. S. A.)

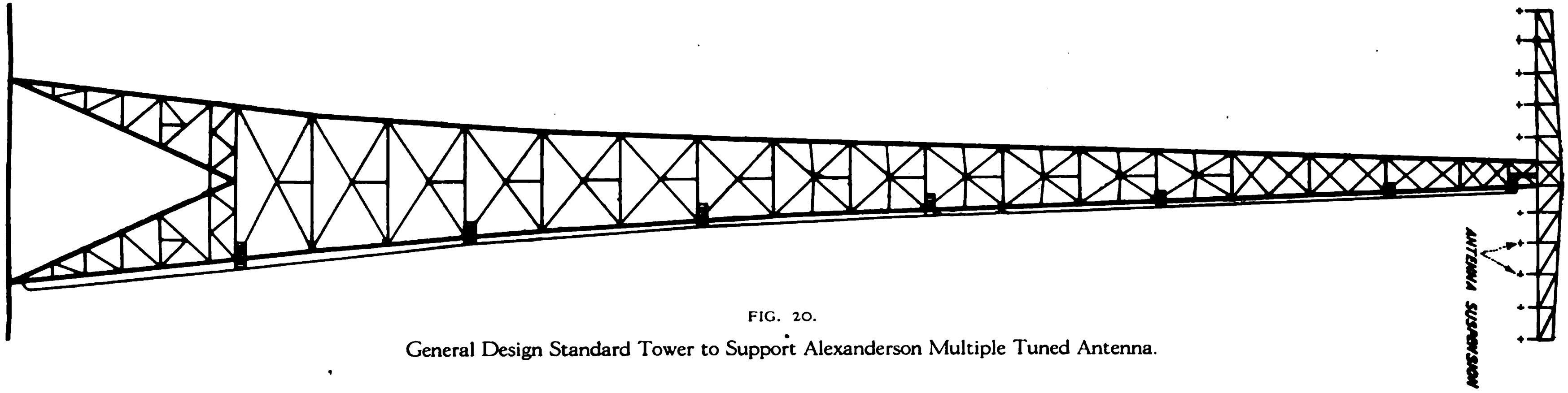


FIG. 20.

General Design Standard Tower to Support Alexanderson Multiple Tuned Antenna.

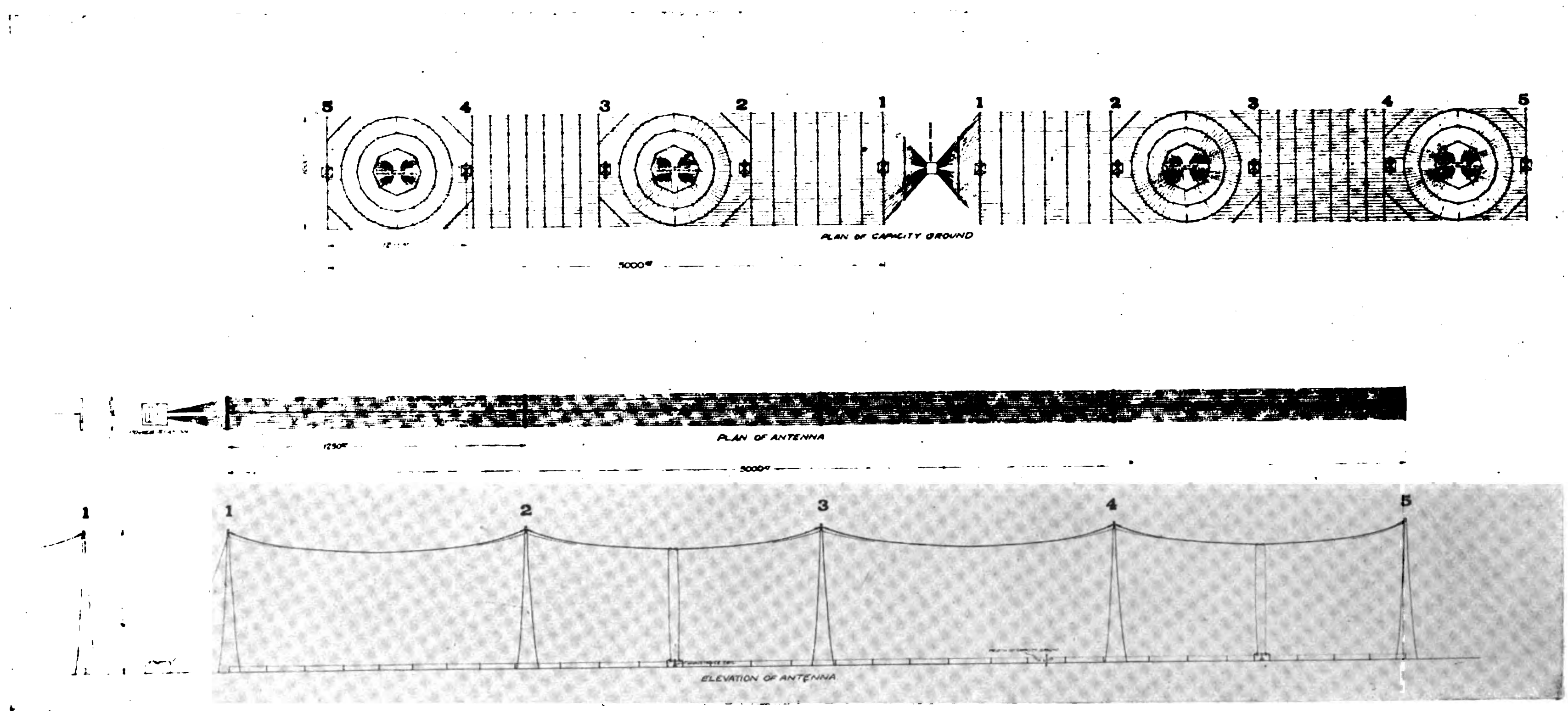


FIG. 21.

Antenna Construction and Counterpoise for Typical 200 Kilowatt Alternator Installation.

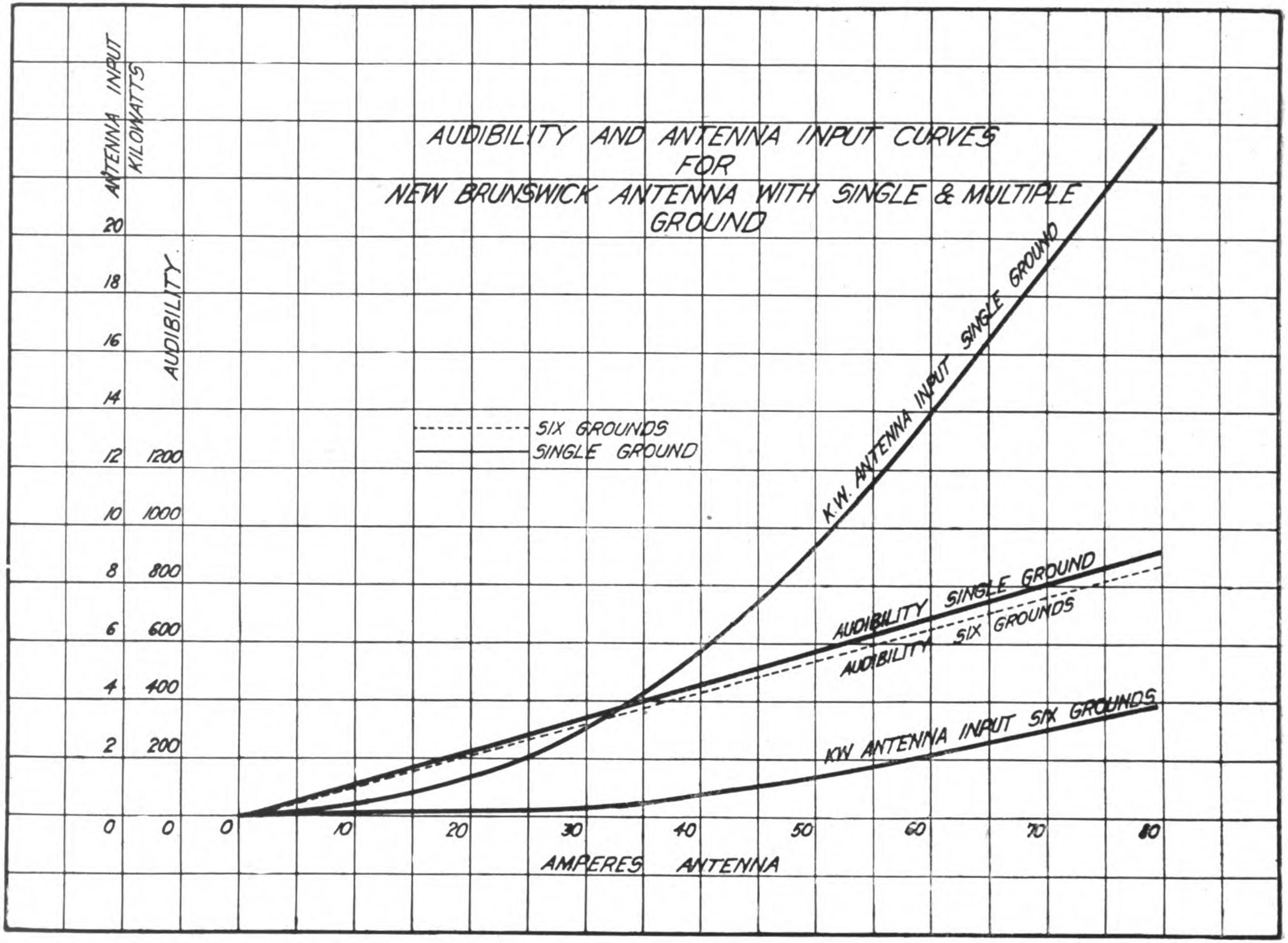


FIG. 22.

Curves Showing Comparative Signal Audibilities Obtained from Alexanderson Multiple Tuned Antenna and the Open-Ended Flat-Top Antenna

PERFORMANCE AND OPERATION OF THE ALEXANDERSON SYSTEM

MULTIPLE TUNED ANTENNA

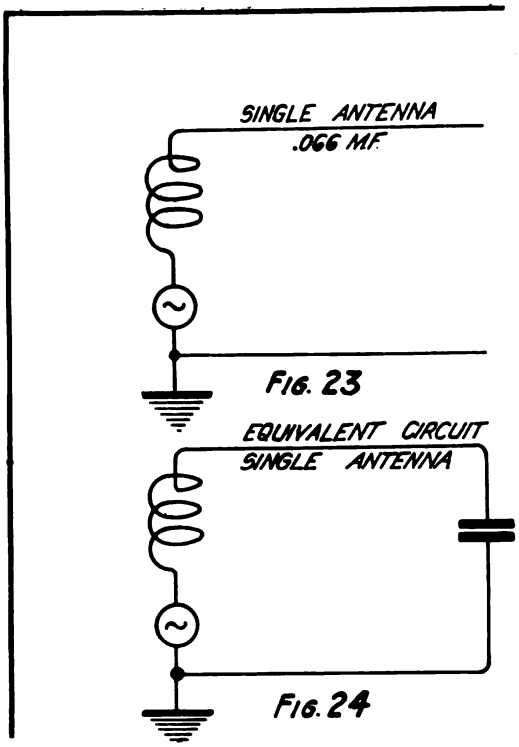
The antennæ commonly used at high-power radio stations may be broadly classified into two types, viz., the long horizontal aerials which are suspended on comparatively low towers, and the vertical, fan or umbrella aerials which are generally supported at great heights. The flat-top antenna was adopted for long distance transmission because it was believed to have marked directional properties and would therefore provide maximum radiation in the direction desired and lesser degrees of signal intensity in all other directions.

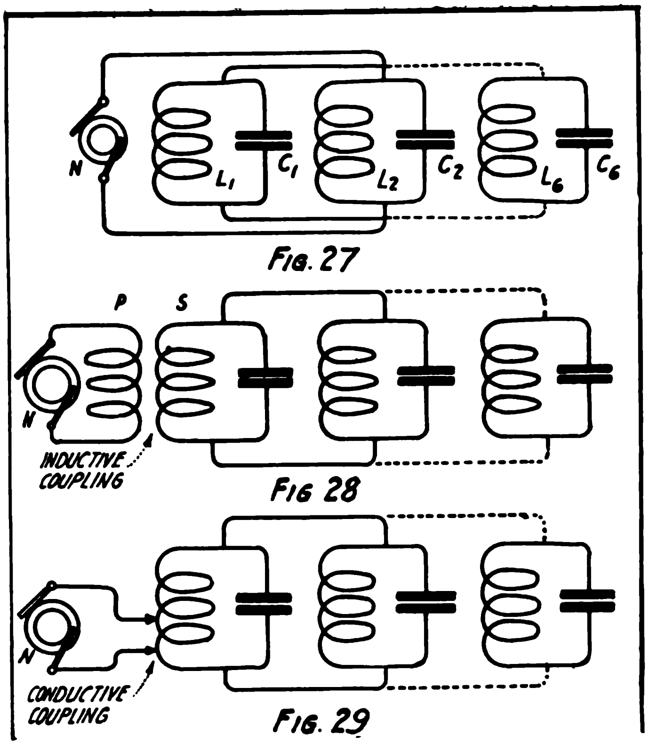
Experiment has indicated, however, that this directional effect disappears at distances beyond 300 miles or so from the transmitter and thus the benefits of directional radiation are realized only in a limited area. *Beyond this* the flat-top antenna has been found to have comparatively high resistance. This may be said to be due to the long path through which part of the ground current has to pass to the far end of the antenna, which is a path of relatively high resistance. This resistance cannot be materially decreased by laying wires in the ground, for because of the inductive impedance of such long wires (at radio frequencies) a large percentage of the ground current will still pass through the earth. It is therefore evident that if the length of the ground path in a radiating system could be reduced, a considerable saving of power would be effected.

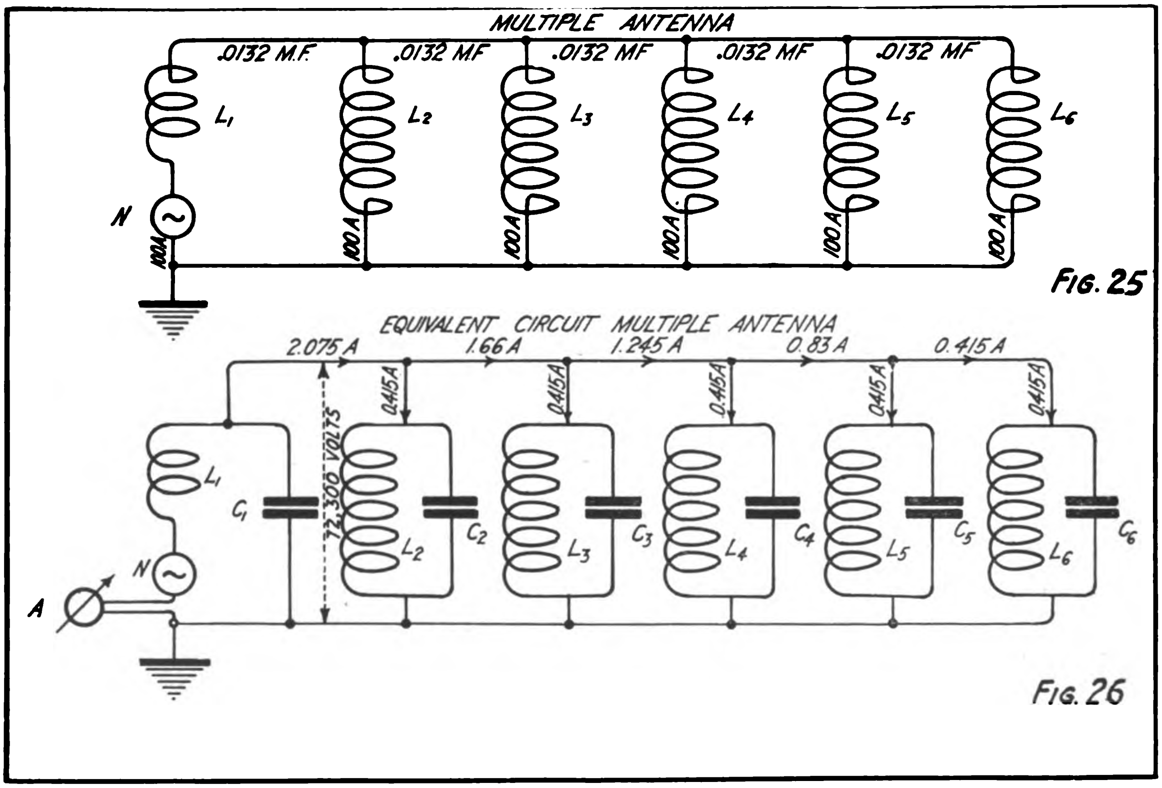
At any given wave length the radiation from an antenna has been found to be proportional to the square of the effective height and the square of the antennae current. The exact relation is $W = \frac{1{,}600\, h^2 i^2}{\lambda^2}$. This points to the desirability of a high antenna, but since the cost of building such a radiating system increases very rapidly with its height, the factor of economy requires that the money expended on a station be apportioned between the cost of the antenna, power apparatus, and maintenance in order to arrive at the lowest total cost for transmission over a given distance. It is obvious that if, by any means the wasteful resistance of the long, low, flat-top antenna, that is, conductive losses, leakage through insulation, etc., could be reduced, and if its radiation properties still could be maintained, then assuming equal power inputs into the two systems, a station using a long, low and relatively cheap antenna could produce the same signal strength as that from a high and costly antenna.

The multiple tuned antenna devised by Mr. Alexanderson brings about a marked decrease in the ground resistance of a flat-top aerial. His antenna can be compared to a station using a number of small antennae connected in parallel, the height of each of which is great compared with their horizontal dimensions. It follows from simple electrical principles that several antennae in parallel will possess a lower joint resistance than a long antenna of the same radiating capacity. The same result may be obtained from the Marconi flat antenna by bringing down leads from the flat-top, at regular intervals, to the ground through appropriate tuning inductances. With this construction it will be seen that the antenna charging current has a much shorter path through the down leads than it had with the former design.

The improved efficiency of the multiple tuned antenna has been amply demonstrated at the New Brunswick station where the resistance of the Marconi flat-top has been reduced from 3.7 ohms to 0.5 ohm with the consequent saving of power pointed out on page 11.







FIGS. 23 TO 29.

Fundamental and Equivalent Circuits of Flat-top Antenna and Alexanderson Multiple Tuned Antenna.

COMPARISON OF RADIATING QUALITIES

The curves of Fig. 22 show the results of a series of experiments conducted between New Brunswick, N. J. and Schenectady, N. Y., with the object of comparing the relative signal audibilities ampere for ampere in the old *antenna with a single ground* and the Alexanderson *antenna with multiple grounds*. The results show quite conclusively that with the same current in a flat-top antenna and in a multiple tuned antenna, substantially equal audibilities are obtained at the receiving station. However, the power required by the plain antenna for a given number of amperes is very much in excess of that fed to the multiple tuned antenna for the same total current. Thus as the curve shows, to put a total of 70 amperes in the branches of the multiple tuned antenna with six grounds, requires but 3 K. W., whereas with the flat-top antenna and a single ground, 18½ K.W. are required. This is of course a very small proportion of the total output available at New Brunswick. The values shown in the curve should not be taken as indicative of those used in daily operation.

THEORETICAL COMPARISONS

The points of distinction between the two types of antennae may become evident from the following comparative analysis. Thus the *flat-top* antenna with single ground is shown in Fig. 23. The equivalent circuit resolved into lumped or concentrated values of inductance and capacitance is shown in Fig. 24. The schematic circuit of the Alexanderson antenna is that of Fig. 25 where L_1, L_2, L_3, L_4, L_5, L_6 are current paths between the flat-top and the earth. The inductance of each down lead is made six times the capacitive reactance of the flat-top at the frequency of operation selected. The capacitive reactance of the flat-top is thus neutralized at six places. The circuit is therefore the equivalent of *six independent radiators* operating in parallel.

The equivalent circuit of Fig. 25 is that of Fig. 26, which is an artificial circuit comprising a number of parallel resonance circuits adjusted to the frequency of the alternator N. The branches L_1 C_1, L_2 C_2, L_3 C_3, etc., which are in shunt to one another are fed by the alternator. When each branch is tuned to the frequency of the alternator it will follow the well-known laws for parallel resonance. A large current will flow back and forth between the inductance and the condenser, and the alternator will simply supply power to compensate the resistance losses of the circuits. These large currents are directly due to the high voltages maintained across the inductance and the capacity, when the circuit is tuned for resonance. These voltages may be calculated when the value of inductance or capacitance and the current flowing therein are known.

If a parallel resonance circuit had no resistance, the conditions for parallel resonance would be strictly the same as for series resonance. These conditions are, however, very closely realized in the parallel circuit. In series resonance the e. m. f. on the condenser is equal and opposite to that of the coil and thus there is a large flow of current between the condenser and coil. There is also a large current flowing between the condenser and the coil in parallel resonance, but viewed from the standpoint of the feed or power supply circuit, the feed current is simply the difference of the currents in the condenser and the coil.

The resistance of a parallel-resonance circuit, in radio, is often treated as a negligible quantity. This resistance, however, assumes considerable importance in the multiple antenna as it determines the power taken from the alternator. Thus if the wasteful resistance of each branch in a multiple tuned antenna of six branches is 2.7 ohms, their joint resistance is $2.7/6 = 0.45$ ohm (assuming equality) and it is this resistance *plus the radiation resistance of the entire antenna* system through which the alternator works.

It is obvious that the alternator can be connected as in Figs. 27, 28 and 29 with the same effect

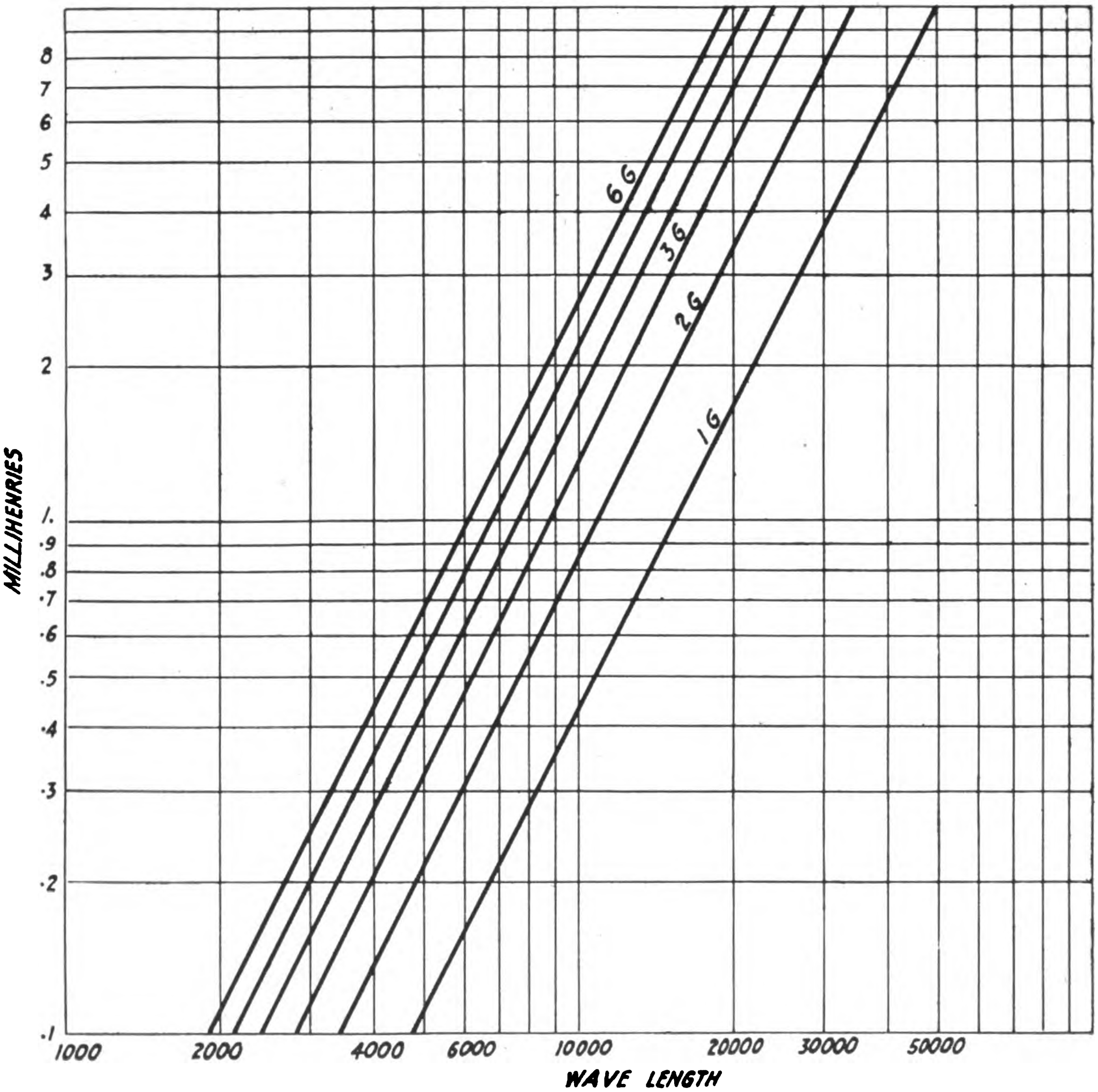


FIG. 30.
Graphs Showing Inductance Required to Tune the Multiple Tuned Antenna at New Brunswick to Different Wave Lengths.

as shown in Fig. 26. Thus in Fig. 27 the alternator terminals are connected in shunt to the parallel resonance circuits. In Fig. 28 the alternator output is fed to the antenna through the inductive transformer P S. In Fig. 29 an auto-transformer connection is employed.

MULTIPLE TUNING

In order to obtain resonance between the alternator and the several radiators of the multiple antennae of Figs. 25 to 29, the joint reactance or impedance of the down leads L_1, L_2, L_3, L_4, L_5, L_6, must be chosen to equal the capacitive reactance of the flat-top at some particular frequency. Hence with multiple tuning at six points the reactance of each down lead, for a given wave length (or frequency), must be six times the capacitive reactance of the whole antenna.

The method of computing the inductance in the down leads for a given wave length is as follows: We may take as a representative example the capacitance of the New Brunswick flat-top antenna, which is a long low aerial of the Marconi type. Its capacitance as measured is 0.066 mfd. Assume that operation is desired at 15,000 meters.

The oscillation frequency,

$$N = \frac{30,0000,000}{15,000} = 20,000 \text{ cycles}$$

The capacitive reactance of 0.066 mfd. at 20,000 cycles

$$= \frac{1}{2 \pi N C}$$

$$= \frac{1}{6,2832 \times 20,000 \times 0.000,000,066}$$

$$= 120.5 \text{ ohms.}$$

The inductance required to neutralize the capacitive reactance is found from the relation

$$L = \frac{X}{2 \pi N}$$

$$= \frac{120.5}{6.2832 \times 20,000}$$

$$= 0.000,958 = 0.958 \text{ millihenry}$$

The total inductance of each down lead should then be 6 x 0.958 = 5.74 millihenry; and the reactance of each down lead, 6 x 120.5 = 723 ohms.

Curves may be prepared to give the values of inductance required to tune the multiple antenna with various number of grounds at different wave lengths. If then the line coils be calibrated for different numbers of turns at different frequencies, it is a relatively simple matter to set these inductances to the correct value for any wave length. A series of curves showing the inductance required to operate the New Brunswick antenna at various wave lengths are given in Fig. 30. These are cited merely as illustrative examples.

FEED RATIO

The term "feed ratio," for convenience, has been applied to express the ratio of the total current in the six radiators of the multiple antenna to that flowing in the down lead of the branch to which the alternator is coupled. Assume that equal inductances are inserted in each down lead. With all other conditions equal, the same current will flow in each of the six circuits when supplied with energy at the frequency which produces resonance.

Thus if the ammeter A, when connected in series with the station down lead, Fig. 26, indicates 100 amperes (at resonance), and the same current is obtained in each branch, the total antenna current is 6 x 100 = 600 amperes.

The feed ratio is then equal to

$$\frac{\text{Total Current}}{\text{Current in the station down lead}}$$

which in this case $= \frac{600}{100} = 6:1$

It is of interest to note that the above feed ratio is only maintained when the inductance in all the down leads is equal. Assume for example, that the inductive reactance in the branch through which the energy is supplied is decreased and the frequency of the alternator is raised for resonance. Assume also that the feed ratio previous to this change is 6:1, the wave length 15,000 meters, the

frequency 20,000 cycles, and the inductive reactance at each down lead 723 ohms. If now the wave length is reduced to 14,500 meters, the frequency increases to 20,700 cycles. This represents an increase of 700 cycles, which is 3½% of the original frequency of 20,000. It may be shown that 1% change in frequency requires a 2% change of inductance for resonance. Hence the inductive reactance in the circuit for 20,700 cycles is 100%—7% or 93% of the value at 20,000 cycles; that is, 93% x 723 = 672 ohms.

Now if the five line coils to earth are left unchanged and since each has an impedance of 723 ohms at 20,000 cycles, or multiple impedance of 723/5 = 144.6 ohms, the impedance at 20,700 cycles obviously is 20,700/20,000 x 144.6 = 149.6 ohms. The new feed ratio is evidently proportional to the two impedances or 672/149.6 = 4.49:1.

The value of this determination lies in the fact that upon changing the wave length by tuning at the station down lead only, the new feed ratio can be computed, thus enabling the operator to ascertain the correct feed current necessary to maintain a given total value of antenna current.

PHASE DIFFERENCE

After viewing the physical aspects of the antenna layout in Fig. 24 it might appear that a disturbing phase angle would exist between the currents in the radiating circuit embracing the

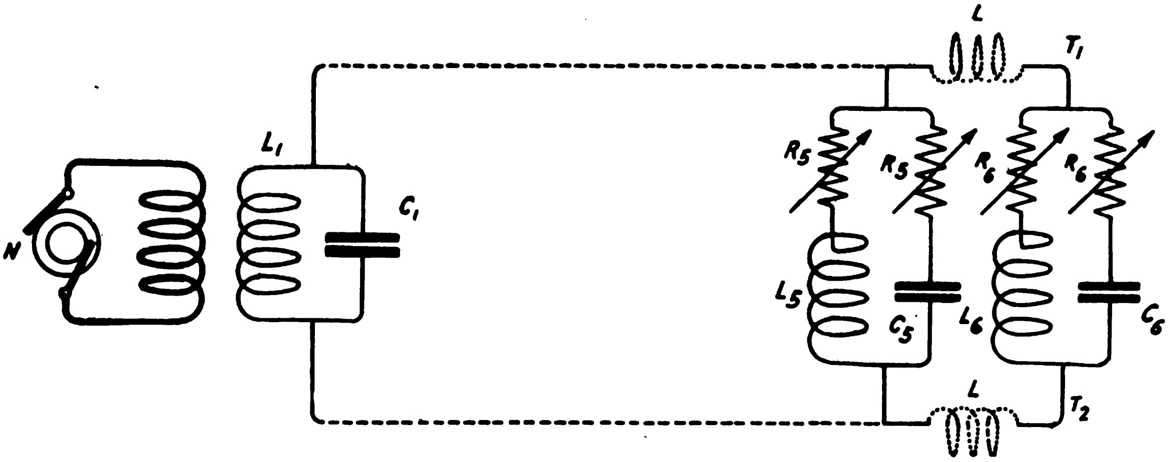


FIG. 31.
Equivalent Circuit of Multiple Tuned Antenna for Computation of Phase Difference.

alternator, and those in the radiators placed at increasing distances from the power source. It can be shown, however, that for all practical purposes the currents in all of the down leads are substantially in phase. Thus in Fig. 31, the branch L_6 C_6, since it is a tuned circuit, operates at unity power factor and therefore may be treated as a non-inductive resistance of a value equal to

$$\frac{L}{C\,R}\left(\text{or}\,\frac{1}{R\,(2\pi N^2)\,C^2}\right)$$

If (at λ = 15,000 m.) C_6 = 0.011 mfd., L_6 = 0.00574 henry and R_6 = 2.71 ohms, then the impedance of any single branch to the e. m. f. impressed thereon is equal to

$$\frac{0.00574}{0.000,000,011 \times 2.71} = 192,500 \text{ ohms approximately.}$$

Since the circuit L_6 C_6 R_6 is in resonance with the e. m. f. impressed at T_1 T_2, the current in it is also in phase with the impressed e. m. f., which may be considered to operate through a non-inductive resistance of approximately 192,500 ohms.

Let now the inductance of the flat-top between the fifth and sixth branches be represented by L. The value of L is one-fifth of the total flat-top inductance without loading and in the case of the New Brunswick antenna is approximately 0.00013 henry. We then have in the last branch (L_6 C_6) a current which lags behind the current flowing in L_5 C_5 by the angle Θ where

$$\tan \Theta = \frac{2 \pi N L}{R}$$

$$= \frac{6.2632 \times 20.000 \times 0.00013}{192.500}$$

$$= \frac{1}{11,780} \text{ (which is negligibly small)}$$

The phase difference between the sixth and fifth radiator is thus negligible. The phase difference between the currents in branch L_1 C_1 and branch L_6 C_6 is five times as great, but it is still of negligible importance. The currents in the six radiators are therefore in substantial phase, the effect of the inductance between branches is negligible, and the charging currents which are measured currents in the down leads can be considered to be in phase. Since the length of the antenna is but a fraction of the wave length employed and the phase difference is slight compared with the wave length, no appreciable directive effects will be obtained.

ANTENNA VOLTAGE

The antenna voltage may be computed when the equivalent capacitance of one section and the current in the station down lead, or the total antenna capacitance and total antenna current are known. This is obtained from the relation, $E = \frac{1}{2 \pi N C}$ or $E = \frac{1}{X}$ where X is the capacitive reactance of the antenna at some frequency.

Using the values in the discussion above, assume that I as measured by an ammeter in the station down lead is 100 amperes. Then since the capacity reactance to be neutralized by the down lead is one-sixth of the whole capacity or 0.011 mfd., then

$$E = \frac{100}{6.2832 \times 20,000 \times 0.000,000,011}$$

$$= 72,300 \text{ volts}$$

A current of 100 amperes performs the same functions in each of the remaining branches, so that the whole antenna is maintained at a voltage of 72,300 volts by six separate currents, all in phase, of 100 amperes each. Since the multiple impedance of the six branches, as shown above, is 120.5 ohms, the total antenna current is 72,300/120.5 = 600 amperes. This is merely a further proof of the assumption made at the outset.

As previously cited the branches of the multiple antenna follow (except in one respect explained below) the laws of parallel resonance circuits with lumped inductance and capacitance, and the current supplied to any branch by the main or power supply circuit is at any instant the algebraic sum of the currents in the capacity and the inductance. If there were no resistance in the branch antenna it would have infinite impedance to the power supply at resonance and no current would flow in the feed circuit after the initial e. m. f. has been applied. In the actual circuit there must, however, be some resistance and the energy for heating this resistance must be supplied by the alternator, that is, the alternator makes good this loss of energy.

The branch circuit of Fig. 30 at N = 20,000 cycles, C = 0.011 mfd., L = 0.00574 henry and R = 2.71 ohms, was shown to have an impedance of approximately 192,500 ohms. The antenna charging voltage at 100 amperes is approximately 72,300 volts. The energy current supplied by

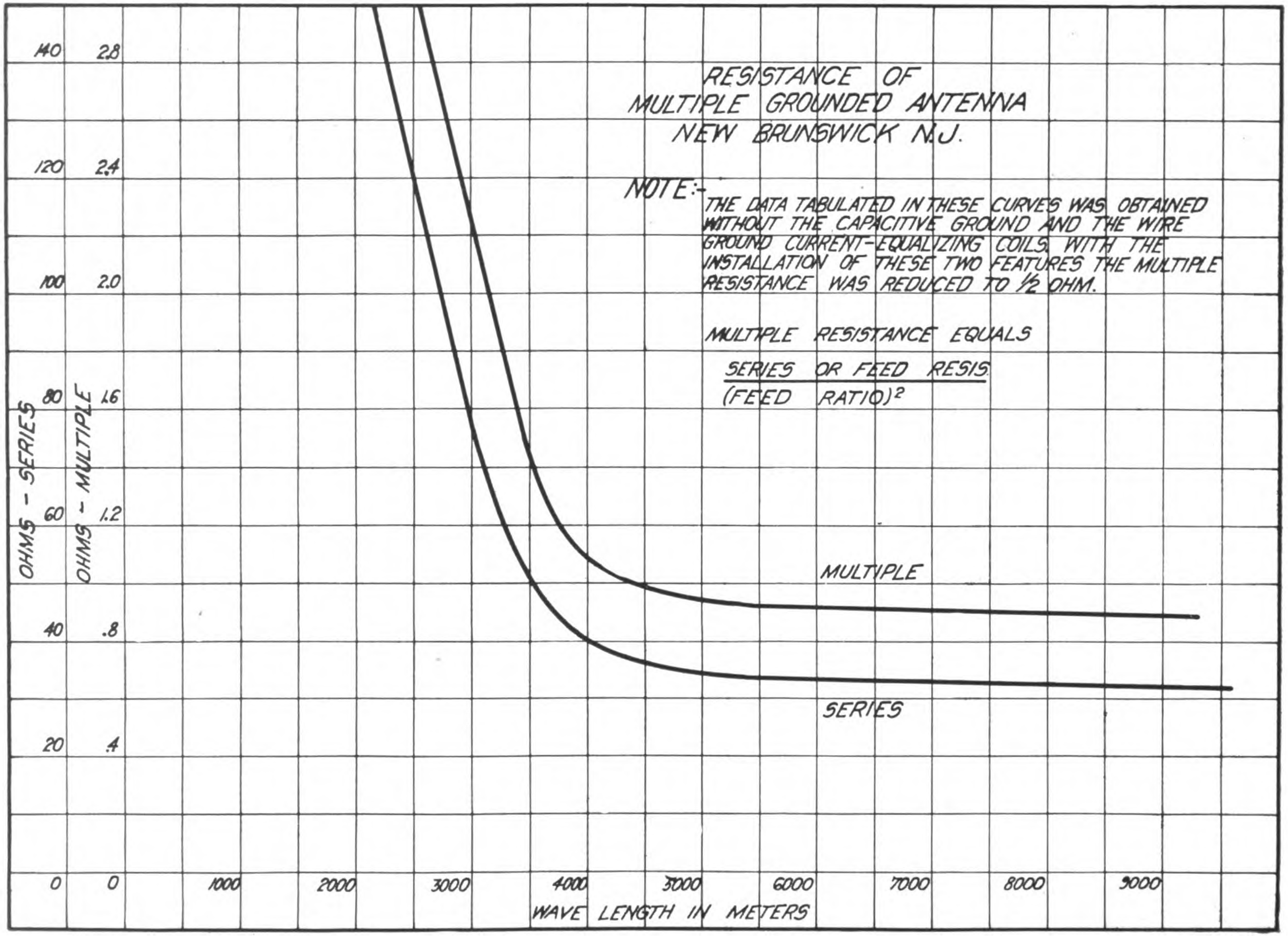


FIG. 32.

Comparison of Multiple and "Series" Resistance of Alexanderson Multiple Tuned Antenna.

the power source to one branch is therefore 72,300/192,500 = 0.375 ampere. The power supplied to each branch is 72,300 $\times$ 0.375 = 27.1 kilowatts and to the six branches (assuming equality throughout) 6 $\times$ 27.1 = 162.6 kilowatts.

The foregoing method of computation while correct for parallel resonance circuits with lumped inductance and capacitance from which no radiation takes place, requires some modification when the phenomena of radiation from the multiple antenna is considered. Thus, in the multiple antenna, the radiation resistance, whatever its value, may be said to be common to all six antennae, whereas the ground and coil resistances belong to the different antennae individually. The combined circuit of the multiple antenna can therefore be represented by a radiation resistance common to all antennae which is in series with a group of six wasteful resistances connected in multiple.

Thus assume now that the radiation resistance of the individual radiators in the multiple antenna (at λ = 15,000 meters) is 0.06 ohm and the ground and coil resistance of each antenna individually, 2.63 ohms. A current of 600 amperes works through 0.06 ohm radiation resistance, while 100 amperes flow through each of the 2.65 ohm resistances. The consumption of power in radiation is $600^2 \times 0.06$ = 21.6 K.W., and in each branch $100^2 \times 2.65$ = 26.5 K.W., or 6 $\times$ 26.5 = 159 K.W., in the six branches. The total consumption is therefore 180.6 K.W.

The point to be brought out is that if the radiation resistance of 0.06 ohm was added to the wasteful resistance in each radiator, and the energy consumption computed therefrom, the result would be too small. Thus assuming that the total resistance of each antenna was taken as 2.65 + 0.06 or 2.71 ohms, the power in each radiator would be 27.1 K.W. and in the six branches, 162 K.W., but, as just shown, the correct value, when the radiation resistance is treated properly, is 180.6 K.W.

The multiple antenna may be treated in another way. With a total power consumption of 180 K.W., the power supplied to each antenna is 30 K.W. and the energy current consumed by each oscillating circuit at 72,300 volts is 0.415 ampere. Thus while the total oscillating current is 600 amperes the energy current which flows horizontally from the power source is 2.075 amperes. This distribution is shown by the arrows Fig. 26. In other words the energy fed to the system by the first tuning coil in the form of 100 amperes at say 1800 volts is transformed in the first oscillating circuit to 72,300 volts (in the case of the particular problem cited) and distributed as in a transmission line from which 0.415 ampere at 72,300 volts is drawn at five places.

MULTIPLE RESISTANCE

When the inductance in each of the down leads has been adjusted to provide resonance with the alternator and the feed ratio has been determined, the multiple resistance of the Alexanderson antenna can be computed from simple measurements taken within the station house.

The process is as follows: Measure the current in the station down lead at resonance and then measure the open circuit voltage of the alternator (at the transformer secondary). The voltage divided by the current gives the "series" resistance of the antenna from the standpoint of a load on the alternator. This resistance is evidently the combined resistance of the alternator and the "series" resistance of the antenna system. The resistance of the alternator must be obtained from a separate measurement and subtracted from this value to give the "series" or load resistance of the antenna system.

Thus if the open circuit voltage of the alternator transformer is 2000 and the current in the down lead is 100 amperes, the resistance of the alternator plus the "series" antenna resistance is obtained from $R = E/I$ or $R = 2000/100 = 20$ ohms.

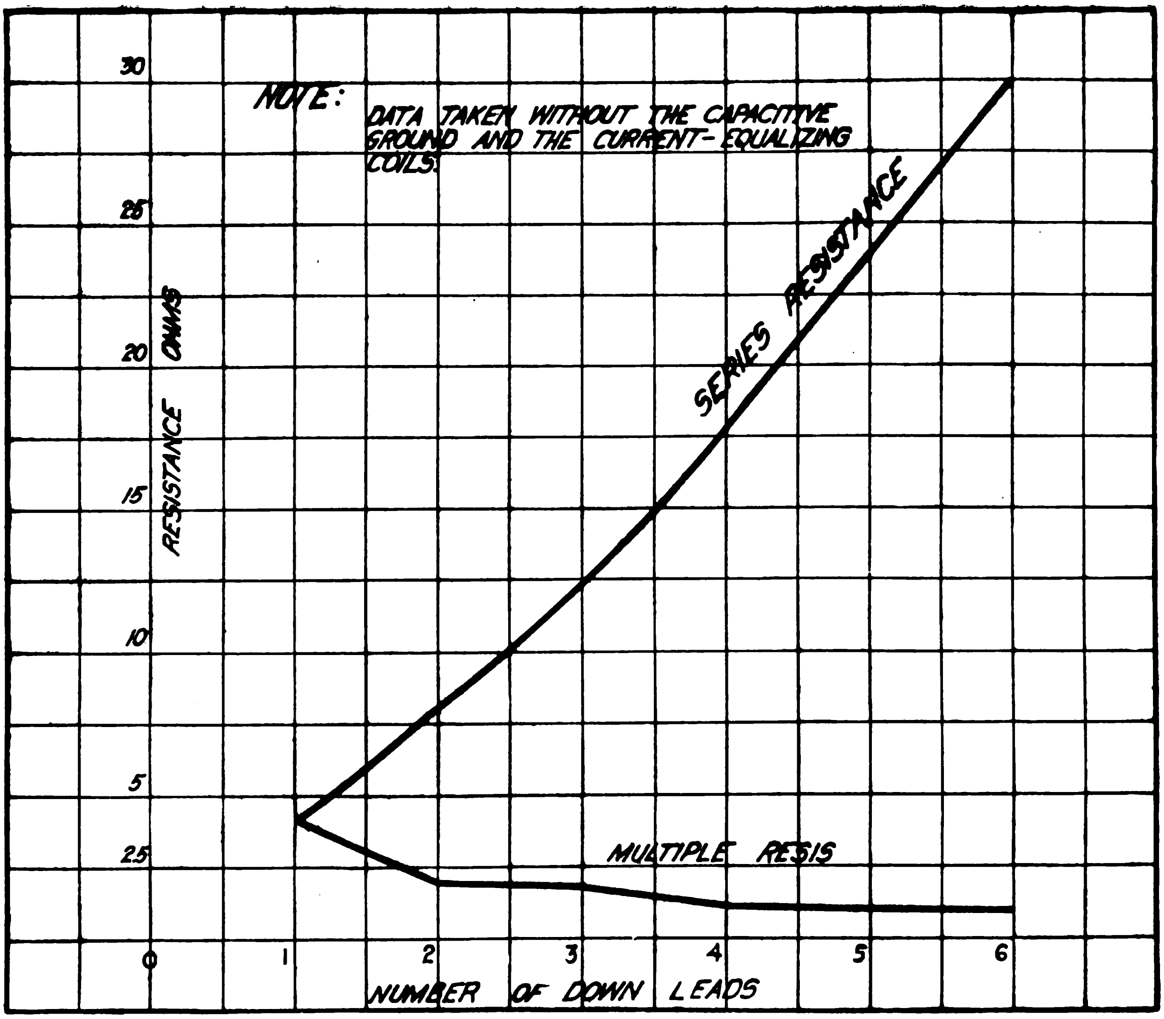


FIG. 33.

Graphs Showing "Series" and Multiple Resistance, New Brunswick Antenna with Different Numbers of Down Leads.

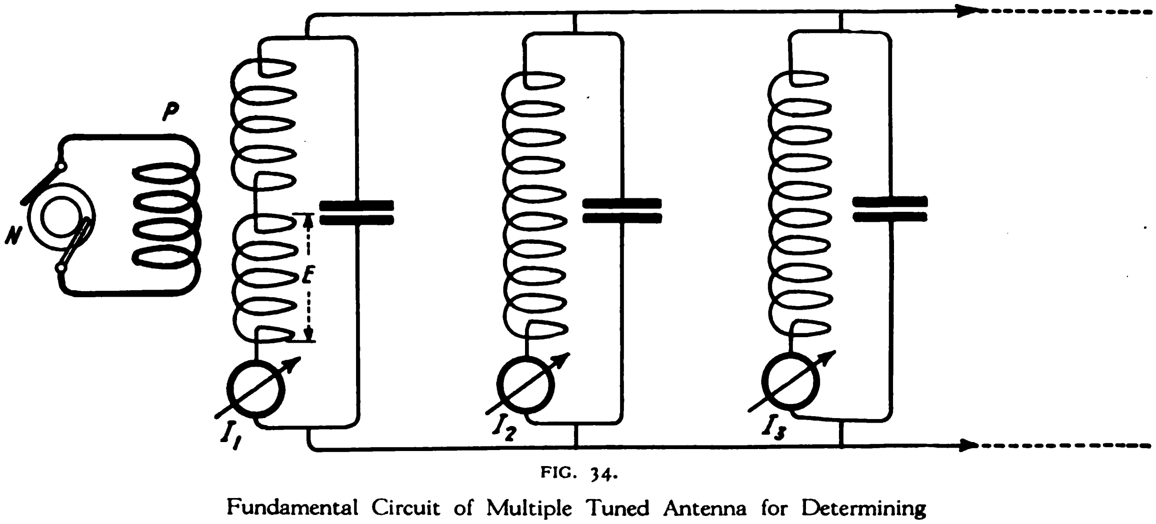


FIG. 34.

Fundamental Circuit of Multiple Tuned Antenna for Determining the Distinction between "Series" and Multiple Antenna Resistance.

Assume that the alternator resistance (from the standpoint of the transformer secondary) as obtained from previcus measurements is 2 ohms; then the series antenna resistance (considered as a load on the alternator) is $20-2=18$ ohms. The multiple resistance of the antenna is then equal to

$$\frac{\text{Series Resistance}}{\text{Square of the Feed Ratio}}$$

which in the problem above $=\frac{18}{6^2}=0.5$ ohm. Proof of this formula is given below.

A set of curves showing the comparative values of these two resistances at the New Brunswick station for wave lengths between 2500 and 9000 meters are shown in Fig. 32. Thus at $\lambda=8600$ meters, the series resistance is 32.5 ohms and the multiple resistance 0.9 ohm. It is the latter value that must be used to compare the multiple tuned antenna with the common antenna with single ground. Curves showing the decrease of multiple resistance at New Brunswick with increase of the number of tuning points are given in Fig. 33. It is to be noted that the data for these curves and also that of Fig. 32 was taken without the capacitive ground and the current equalizers described on page 13.

In making measurements as above the transformer must be regarded in all respects as a part of the alternator, that is, the open circuit voltage of the transformer secondary, and the resistance of the alternator from the standpoint of the transformer secondary must be treated as the voltage and the resistance respectively of the alternator.

A proof of the formula Multiple Resistance $=\frac{\text{Antenna Series Resistance}}{(\text{Feed Ratio})^2}$ may be had from the following simple analysis. Reference should be made to the equivalent circuit Fig. 34, which is assumed to be made up of a number of radiating systems in parallel, all tuned to resonance with the alternator N.

Let E = open circuit voltage of transformer secondary.
I = current in the station down lead at resonance.
R_a = the effective alternator resistance from the standpoint of the secondary.
r = the "series" resistance of the external or antenna circuit considered as a load on the alternator.

Then $E = I(R_a + r)$

from which $r = \frac{E}{I} - R_a$

(R_a is obtained from a separate measurement).

The power consumed in the "series" or load circuit external to the alternator is then,
$W = I^2 r$.

Consider now the resistance of the complete antenna from the standpoint of several radiators in parallel:—
Let F = feed ratio.

Then FI = total antenna current in the several radiators.

Also let R_a = multiple resistance of the several radiators in parallel.

Then, the total energy in the several radiators is equal to the product of the multiple antenna resistance and the square of the total antenna current, or,

$$W = (F\,I)^2 R_m.$$

This energy obviously is the same as that consumed in the circuit external to the alternator, which as shown before, $= I^2 r$.

$$\text{Hence } (F\ I)^2 R_m = I^2 r$$

$$\text{from which } R_m = \frac{r}{F^2}$$

That is, the antenna multiple resistance is equal to the "series" or "alternator load" resistance divided by the square of the feed ratio. Expressed in terms of all the factors involved

$$R_a = \frac{\frac{E}{I} - R_a}{F^2}$$

It is thus possible to compute the multiple resistance of the Alexanderson antenna from a few measurements made within the station with instruments used in ordinary power work.

Accurate measurement of the current in each down lead is essential, prior to making the above measurements, as equal divisions of current, due to physical factors surrounding the station, cannot always be obtained. Only in this way can the true feed ratio be determined.

GENERAL

The multiple antenna can, under some conditions, be used to advantage with unequal currents through the down leads although, in general, equality of currents gives the lowest resistance. This is apparent from the fact that with unequal division some of the current has a longer path to travel than with equal division, making that particular branch of higher resistance. This also is obvious from the fact that if a given amount of current is to be passed through parallel conductors their joint resistance will be less if the division of current is in inverse proportion to each path.

Unequal division of current is an advantage under two conditions. First the "series" or "load" resistance of the antenna can be adapted to the voltage of the alternator, if the alternator voltage cannot be adapted to the antenna resistance. Second, by allowing unequal division of current the wave length of the system can be changed in a much simpler manner than when equal division is maintained. Each change of wave length clearly requires a change in the inductance of all the down leads to maintain equal current division. If the inductance in all down leads is not the same, the current will divide itself in inverse proportion to the inductance of each path.

Further consideration will reveal that for wide changes of wave length it may be advisable to disconnect some of the down leads.

CALIBRATION OF GROUND INDUCTANCES

In order to compute the amount of inductance that is necessary in each down lead at some given wave length, the capacity of the antenna must be measured by the ordinary processes and its capacitive impedance calculated as shown on page 33. This of course, must be computed for each wave length. The capacitive impedance for any other wave length can be obtained from this value, since impedance is directly proportional to wave length. The inductive impedance of each down lead should then be adjusted, previous to tuning of the alternator, to a value six times the capacitive impedance of the antenna, if six tuning points are used. The inductance of the down leads to the tuning coils can be estimated roughly and the value allowed for when placing the tap on the ground coil.

The inductance of the tuning coils should be computed for different numbers of turns at different wave lengths and plotted in a series of graphs as in Fig. 30. This will simplify the operation of obtaining the correct inductance for any wave length. In case there are no means at hand of cali-

brating the tuning coils, the required number of turns may be selected by trial. The supposed number of turns required can be estimated roughly and connected in all six down leads, but an allowance must be made in the case of the *station down lead* for the inductance of the alternator (or for the inductance of the secondary coil of the transformer). The speed of the alternator may then be varied until resonance is found. If the number of turns selected tune at too long a wave length too much inductance has been inserted in the down leads, and if it tunes at too short a wave length not enough inductance has been added.

CAPACITIVE AND WIRE GROUND SYSTEM

A general description of the earthing system at the New Brunswick station has been given on page 13. In the early experiments it was found that when connection was made from the tap on the down lead inductance to the wire ground, the inner wires carried the greater proportion of current, due to the fact that they offered less impedance than the outer wires. A more equal current distribution was obtained by inserting the equalizing coils between the line inductances and the earth wires as shown in detail, Fig. 15. These coils are in inductive relation and are connected to pairs

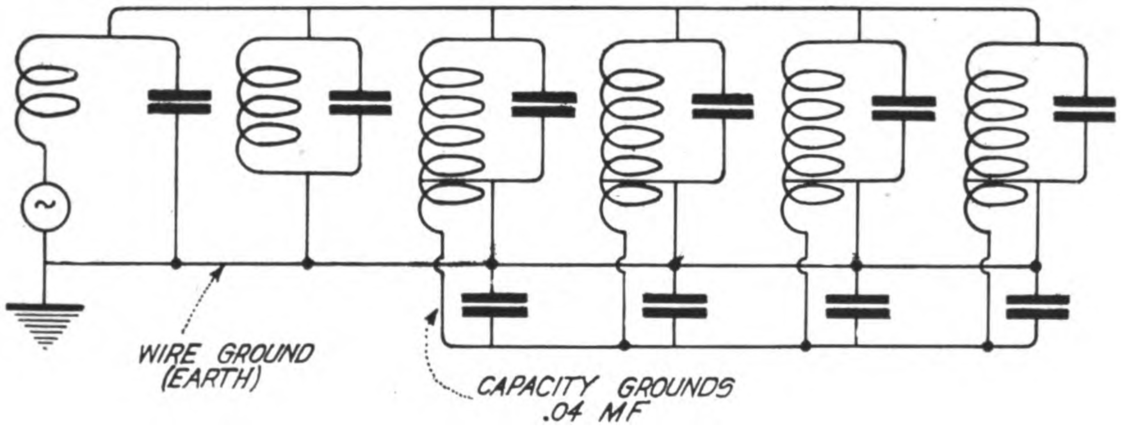


FIG. 35.
Equivalent Circuit Multiple Tuned Antenna, New Brunswick Transoceanic Radio Station.

of the buried wires as there shown. The effect was to increase the impedance of the wires nearest the center and therefore to force practically the same amount of current in the outside wires as in the center wires. This lowered the antenna resistance from 0.9 to 0.7 ohm.

A still better distribution of the earth currents was obtained by installing the counterpoise already shown in Fig. 16. As is shown schematically in detail A, Fig. 16a, the section of the coil above the ground connection may, for purposes of illustration, be considered as positive with respect to the ground and the section below the point at which the ground is connected may be considered as negative with respect to the ground. The capacitive ground may therefore be considered as a combination of a forced and a tuned oscillation circuit. It has the effect of drawing the current from the ground more uniformly, than with the wires lying on the ground or buried beneath the surface. The addition of the counterpoise in the case of the New Brunswick station reduced the antenna resistance from 0.7 to 0.5 ohm.

By suitable tuning, the total current through the down leads may be distributed between the capacitive ground and the wire ground in any desired ratio. If the wire ground is disconnected and the capacitive ground is tuned to take all the antenna current, the capacitive ground then

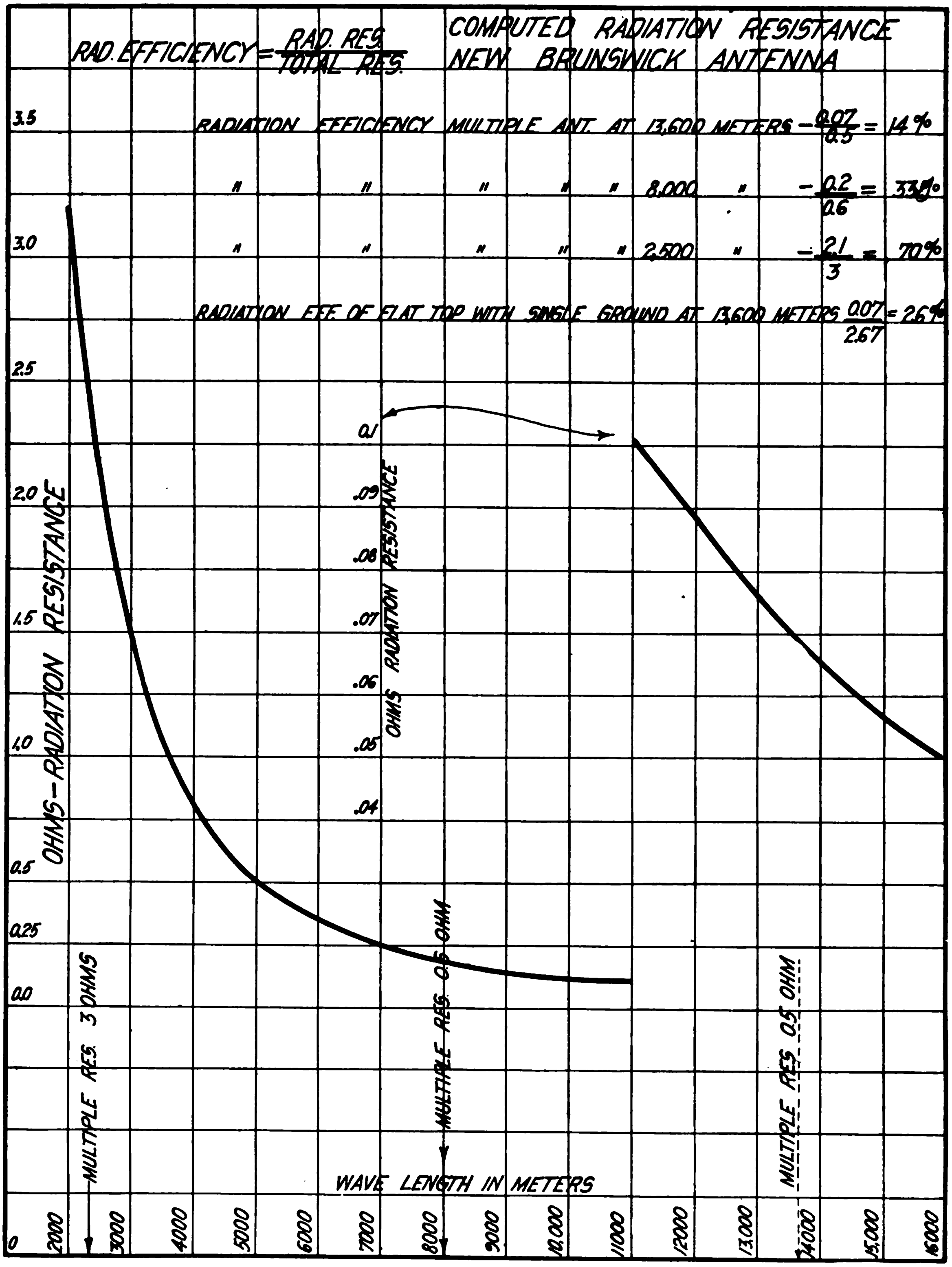


FIG. 36.

Computed Radiation Resistance Multiple Tuned Antenna, New Brunswick Transoceanic Radio Station.

takes on the characteristics of a tuned circuit. In this case the wire ground may be connected to the zero potential point on the coil (which may be found by experiment), under which condition it forms a path to earth for the lightning discharges with no other appreciable effect upon the system. An efficient ratio of current in the wire and capacitive ground is half of total in each. The capacitive ground may be installed in separate units at each tuning point or may be connected together as a single unit as shown in Fig. 16.

Taking into consideration the counterpoise and buried wire ground, the equivalent circuit becomes that of Fig. 35.

It may be well to point out here that the design and construction of the grounding system for the multiple antenna may undergo considerable modifications in future high-power installations. It is probable that the system can be considerably simplified and yet provide a lower total antenna resistance than that obtained at the New Brunswick station.

RADIATION EFFICIENCY

An antenna with a single ground and effective height equal to that of the New Brunswick aerial, can be assigned at the wave length of 15,000 meters a radiation resistance of 0.06 ohm and a total resistance of 2.71 ohms. This is, in fact, about the values that would be obtained in practice. The radiation efficiency is therefore 0.06/2.71 or 2.21%.

As a multiple tuned antenna the resistance of the New Brunswick aerial is slightly under 0.5 ohm, and the radiation efficiency is 0.06/0.5 or 12%. The radiation efficiency of the multiple antenna at this wave length is therefore 12% against 2.21% in the individual antennae.

The radiation efficiency of the multiple antenna is very much higher at the wave length of 8,000 meters which has been found the most suitable for radio telephony. Thus the radiation resistance of the New Brunswick antenna at 8,000 meters is 0.2 ohm and the multiple resistance 0.6 ohm. The radiation efficiency is 0.2/0.6 or 33%.

It is important to note that the New Brunswick antenna may be operated at the wave length of 2,500 meters, although its natural wave length as a flat-top antenna is 8,000 meters. Operation at such short wave lengths obviously would not be possible with the antenna in its old form. The multiple resistance of the New Brunswick antenna at 2,500 meters is 3 ohms, and the radiation resistance is 2.1 ohms. The radiation efficiency is therefore 2.1/3 or 70%, whereas with a single ground antenna the resistance at the same wave length would be about 5.4 ohms, and the radiation efficiency, 2.1/5.4 or 40%.

A curve showing the computed values of the radiation resistance of the New Brunswick antenna, at various wave lengths, is given in Fig. 36. The multiple resistance as actually measured at the wave lengths of 2,500, 8,000 and 13,600 meters is pointed out. The radiation efficiency at these three wave lengths should be noted, and also the comparative efficiencies of the common antenna with the single ground and the Alexanderson antenna with multiple grounds, at the wave length of 13,600 meters.

Although the radiation efficiency of all types of antennae decreases with increases of wave length the smaller absorption obtained at the longer wave lengths offsets this decrease. Efficient wave lengths for trans-oceanic communication have been found to lie between 10,000 and 20,000 meters.

ALEXANDERSON SPEED REGULATOR

As pointed out on page 9, in order to secure a constant output at the alternator and to prevent a diminution of the received current at the receiving station, the speed variation of the radio

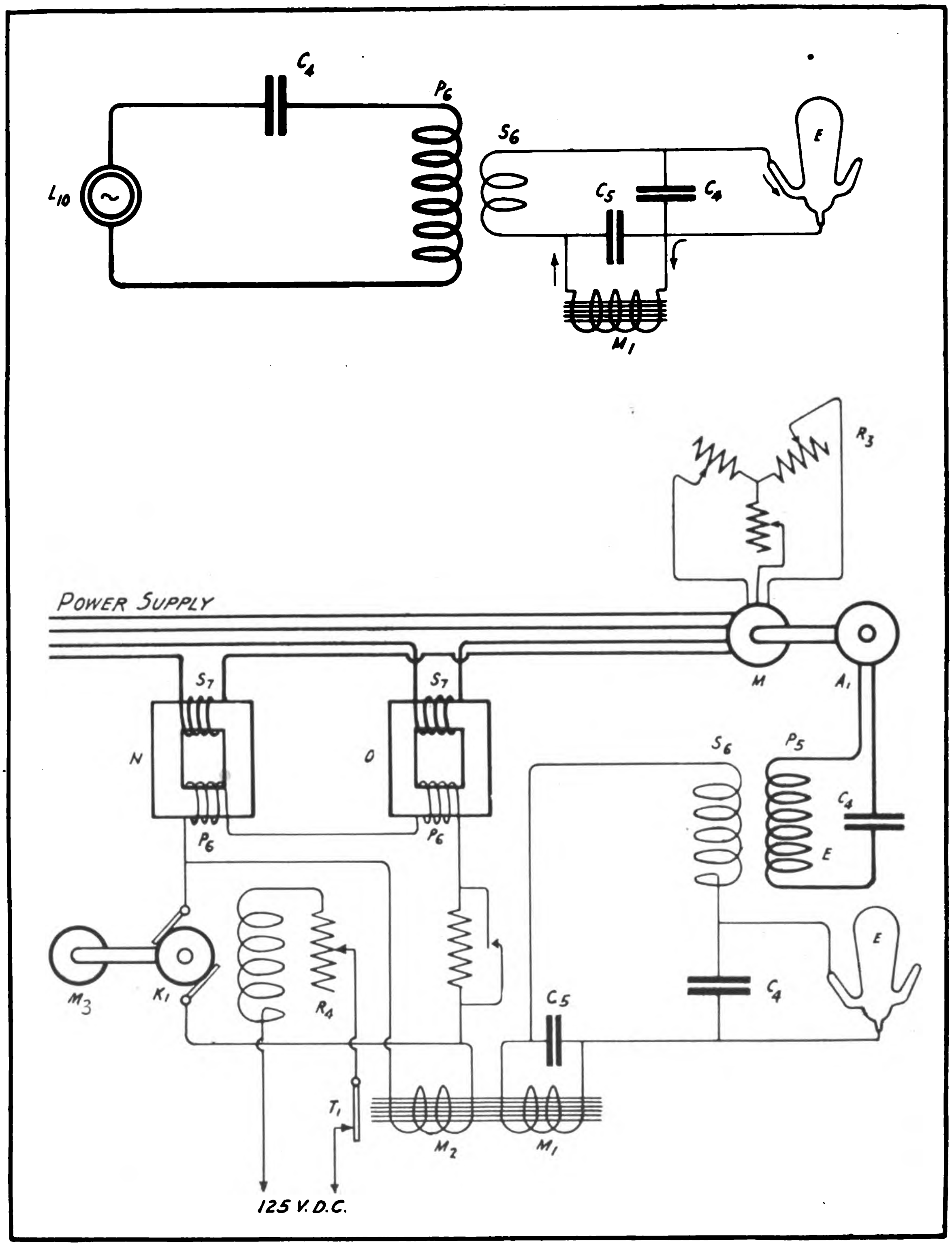


FIG. 37.

Fundamental Circuits of Speed Regulator, of the Alexanderson Radio Frequency Alternator System.

frequency alternator, when signalling, must be maintained within one-tenth of one per cent. It is evident that the governing mechanism to maintain such constant speeds must come into such a critical state, at the motor speed to be maintained, as to cause a high percentage of change in itself for a low percentage change in speed.

The circuits of the Alexanderson speed regulator have been shown in the fundamental station circuit, Fig. 19. They are shown separately in Fig. 37. L_{10} is an armature coil which supplies a constant voltage at the frequency of the alternator. C_4 and P_5 are a capacity and an inductance which are tuned to a frequency slightly above that at which the alternator is to be worked. The coil S_6 is coupled closely to P_5, but not so closely as to affect appreciably the tuning of the resonant circuit. E is a rectifier (of the G. E. Tungar or Mercury Arc type) which is shunted by a condenser C_4 of 0.16 mfd. capacity.

M_1 is an auxiliary control coil of the voltage regulator. The latter through the contacts T_1 acts to control the voltage of a generator K_1. C_5 is a condenser of 1 mfd. shunting the coil M_1. Care is taken that the circuit S_6, C_4, C_5, is considerably off resonance with the frequency of the circuit L_{10}, C_4, P_5, in order that the speed held by the regulator may be changed with the greatest simplicity.

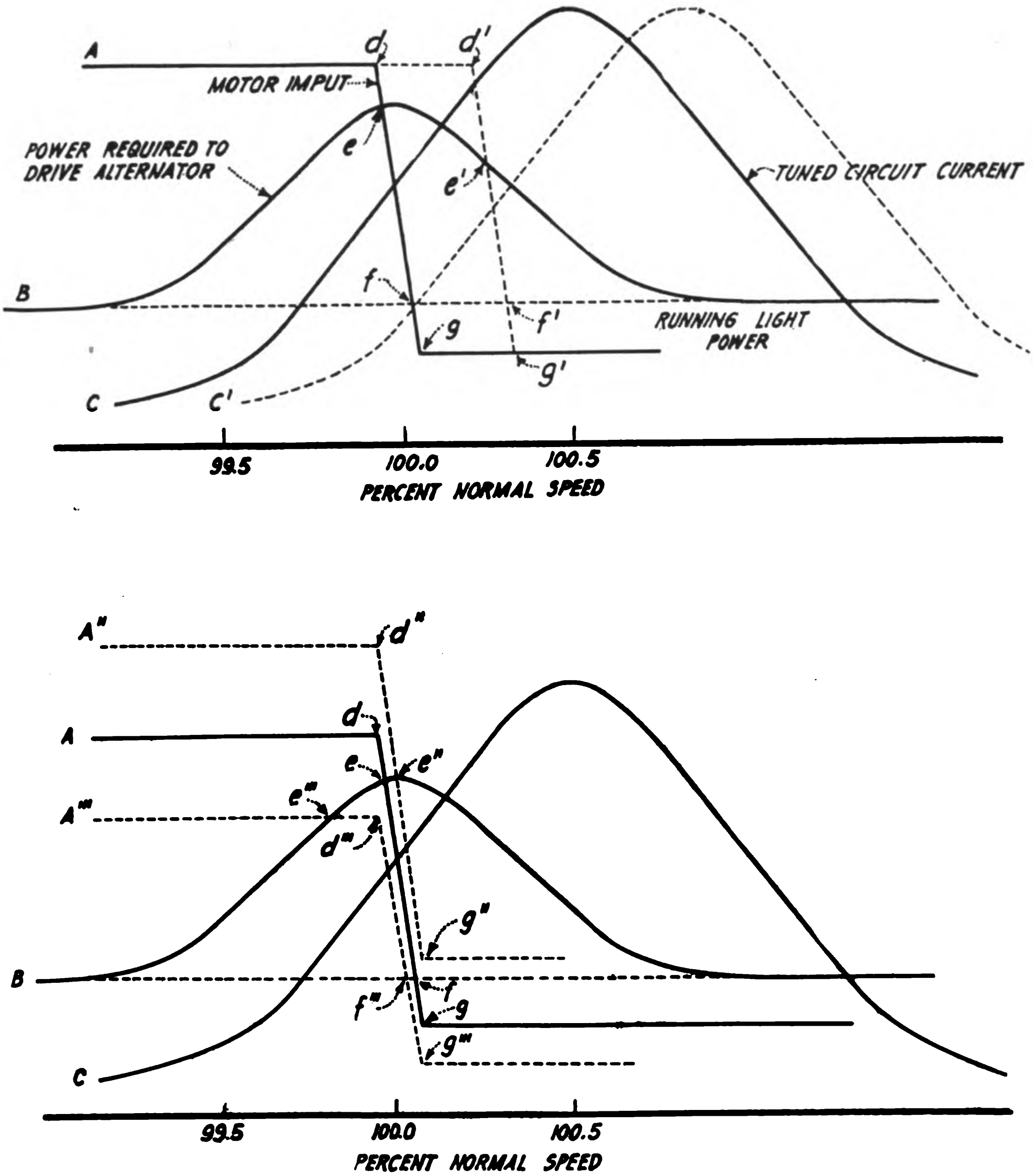
N and O are variable impedances connected in the two phases of the power supply lines. They contain the D. C. control coils P_6 and the variable impedance coils S_7. R_3 is a liquid rheostat connected in the circuits of the rotor.

The generator K_1, which is driven by the motor M_3, is provided with field current from a D. C. source of constant voltage which is varied by the rheostat R_4.

In regard to the functions of the impedances N and O, it may be said, in general, that with zero current in the control coils P_6, their impedance becomes a maximum. If on the other hand the current through P_6 is such as to saturate the cores, their impedance becomes a minimum. Any intermediate value of D. C. control current will vary the A. C. impedance of the coils S_7 accordingly.

It will now be shown how the motor input may be varied inversely as the current fed into the coil M_1 from the resonance circuit brought from a coil in the armature. Since the circuit L_{10}, C_4, P_5, is resonant to a frequency slightly above that of the alternator, it will develop an increased current as the motor M speeds up. This will send a D. C. component through the coil M_1 which assists that flowing in coil M_2; this causes the voltage regulator proper to maintain a lower voltage at generator K_1. This in turn decreases the current through the coils P_6 and therefore increases the impedance in the power supply circuit, tending to decrease the speed of the motor. When the speed falls slightly the rectified component through the coil M_1 decreases, thus causing the voltage regulator to maintain a higher voltage on the generator K_1 and therefore increase the control current through P_6, and thus again decrease the impedance in the power supply circuit. A given mean current is thus maintained through the control coils P_6, the value of which is determined by the value of the current through M_1. The speed of the driving motor is thus held constant.

In order to lighten the duty of the speed regulator proper a special device is provided to compensate for the additional load thrown upon the driving motor when the sending key is closed. In the case of a rotor wound induction motor this may be accomplished by one of two methods. One method is shown in Fig. 19, where a relay, with contacts T_2, shunts a resistance R_2 each time the sending key is closed, increasing the saturation current and thereby reducing the impedance of S_7 by an amount that will compensate for the load imposed by signalling. This compensation evidently is independent of speed variation. The speed regulator has therefore only the variation in the power supply and the irregularities produced by the compensator to take care of.



FIGS. 38 AND 39.

Graphs Showing Certain Characteristics of the Alexanderson Speed Control System.

The second method of obtaining this compensation is to shunt out a certain amount of the rotor resistance R_3 each time the sending key is closed, which increases the power input proportionally. The amount of compensation provided in either case must be set according to the load added to the driving motor by closing the sending key. Either method of compensation has been found satisfactory, although with the first described method the duty imposed upon the compensating relays is less severe.

THEORY OF THE SPEED CONTROL REGULATOR

A series of graphs showing the phenomena involved in the action of the speed regulator are shown in Fig. 38 and Fig. 39.

In curve A, Fig. 38, the "motor input" is plotted against "percent variation of normal speed" with the normal line voltage and frequency and with the resistance R_3 (in the rotor circuit of the motor) properly adjusted to provide the required power. The flat part of the curve to d, indicates the motor input with maximum field on generator K_1, Fig. 37, which is the result obtained with zero current in the coil M_1 of the voltage regulator. It should be noted that the motor input with the speed less than 99.95% normal is well above that required to drive the alternator with the sending key closed. The motor will therefore increase its speed up to point d, where the speed regulator takes hold. From here the motor input drops off rapidly because of the increasing current in coil M_1, (of the voltage regulator) until its curve intersects curve B which represents the power required to drive the alternator at point e. Here the motor input and the power required to drive the alternator are equal and the speed will remain constant.

When the key is opened, the power required to drive the alternator drops off to that indicated by the dotted line and the surplus of power supplied to the motor speeds up the alternator until the motor input has dropped off to a value equal to that required to run the alternator light. This condition is represented at the intersection f at 100.05% normal speed.

Point g represents the point at which the speed regulator has decreased the motor input the maximum amount possible, with minimum field on generator K_1; and for any small increase in speed above this point, the input will be the same as at g. Since here the power required to drive the alternator is greater than that supplied to the motor, the motor will slow down until equality is obtained as at point f with the key open, or as at point e with the key closed. With the speed at point f when the key is closed, the speed will decrease to point e, and when the key is opened again, it will increase again to that represented by f. This speed variation being less than 0.1%, no inconvenience is suffered.

If, however, the characteristics of the speed regulator are such that it lags in action, the speed may fall below e, before the regulator can effectively increase the power input. This will cause a greater variation of speed than would otherwise obtain. "Hunting" may then take place and result in a speed variation greatly in excess of the allowable variation for constant alternator output. This can only be prevented by properly designing the whole set.

The speed held by the regulator at a given alternator frequency may be changed to some other value by retuning the circuit L_{10}, C_4, P_6 through variation of its capacity or inductance. This will change curve A, Fig. 38, which will then maintain the same relation to the curve C, thus providing a different speed at which the power required to drive the alternator will equal the motor input. These conditions are represented in dotted lines in Fig. 38, e′ and f′ representing the speeds held with the key closed and open respectively, and d′ the point at which the speed regulator takes hold.

To obtain proper regulation the speed regulator must be adjusted so the point e will be on the

left or lower side of curve B, for on that side of the curve an increase in speed will incur an increase in load, (as resonance in the alternator antenna circuit is approached) which automatically will tend to keep the speed down. On the other hand if the point e lies on the high side of the curve B an increase in speed will decrease the load which will tend to cause still further increases of speed. This is prevented only by the fact that the speed regulator causes the motor input to fall off faster than the load falls off. Because of the fact that better regulation is secured on the low side of the curve, it is called the *stable side,* and the high side the *unstable side.*

If the power supplied to the driving motor is increased, such as by an increase in line voltage or frequency, or by a change in the setting of the motor circuits (such as a decrease in the rotor resistance of an induction motor) the curve for motor input will rise as to A″, Fig. 39. If the power supplied to the motor is decreased the curve of motor input will fall as to A‴.

The motor adjustment must be maintained so that point g on the motor input curve will be kept well below the power required to run the machine light, (as shown by the dotted lines) and also point d must be kept well above the power required to drive the alternator at maximum tune of the antennae. In case point g is not well below the power required to run the machine light a surge in line voltage or frequency might increase it to g″ where it would be greater and thus cause the alternator to run away when the sending key is left open a short interval. Also if point d is not well above the power required to drive the alternator at maximum tune a slump in line voltage or frequency might decrease it to d‴ and thus cause the machine to slow down to e‴ when the key is closed, with a consequent falling off in signal strength and a swing in the pitch of the received note.

If adjustments are made so that the conditions outlined above are realized, no difficulties are encountered in maintaining a uniform speed at any desired alternator frequency.

MAGNETIC AMPLIFIER

This device already has been described as a variable impedance connected across the terminals of the radio frequency alternator for the purpose of controlling the power input to the antenna circuit. Its characteristics are such that a relatively small current in an excitation winding is enabled to control many hundreds of amperes in the antenna system. The amplifier performs two functions: When the sending key proper is open the alternator is placed on short circuit and the antenna system detuned. The joint effect of these two phenomena is a reduction in antenna current to 9% of its normal value. When the sending key is closed, the alternator assumes substantially its normal voltage, the antenna system returns to a state of resonance and the alternator output flows into the antenna system.

The great advantage of the amplifier over other methods of modulation is that it gives a non-arcing control of the large currents required in high-power radio transmission and therefore permits rapid telegraph signalling. In fact the amplifier has been operated experimentally at speeds in excess of 500 words per minute with perfect success.

An idea of the fundamental actions of the amplifier can be gained from the circuit, Fig. 40 where the two windings designated by A and B are wound on a common iron core. The windings A are connected in parallel and shunted across the radio frequency alternator N. The coil B is an excitation winding which includes both the positive and the negative branches of the flux produced in the windings A, and hence, no voltages are induced in B by the radio frequency currents flowing in A. This is illustrated by the reference arrows in Fig. 41, which show the direction of flux in the amplifier coil at a particular half-cycle of the impressed current. It is clear that the tendency to induce an e. m. f. in one side of the control coil by one branch of A is counteracted by an opposing e. m. f. in the other branch.

It is apparent that should the flux produced in the core by the coil B be sufficient to saturate it fully, the impedance of windings A would become that of a coil without an iron core. On the other hand, with zero current in the winding B, the core will be magnetized by the windings A and the impedance of A will thus become a maximum. In general, in order to obtain large flux variations in the windings A, the opposing ampere-turns in B must be approximately equal to those in A. Utilizing the alternator control circuit of Fig. 40, the problem is to obtain a minimum impedance in the windings A when the circuit to the excitation or control winding is closed and thus short circuit the alternator; and to obtain a maximum impedance when the control circuit is open, so that the alternator may assume within reasonable limitations its normal voltage. In this way the necessary variation of the antenna current for telegraphic signalling is secured.

The characteristics of a magnetic amplifier operated in a given instance as in Fig. 40, are shown in the curve A, Fig. 42, where antenna amperes are plotted against different currents in the excitation

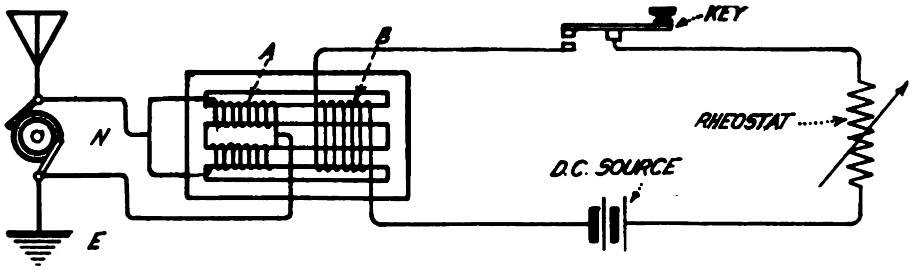


FIG. 40.

Magnetic Amplifier in Simplified Form.

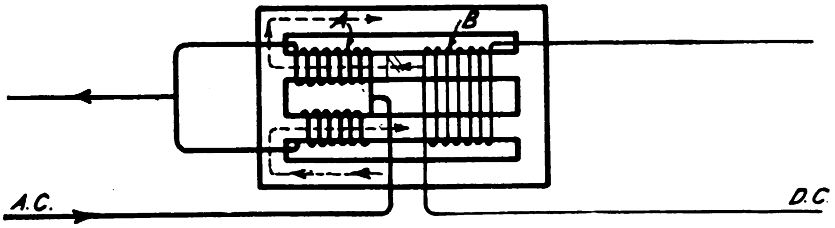


FIG. 41.

Showing Inductive Action of Amplifier Windings upon the Control Winding.

or control coil. The curve A shows incomplete modulation of the antenna current, but it should be mentioned that with this circuit it is possible to secure more complete modulation with stronger currents in the control winding.

A more sensitive control of the alternator output to the antenna system can be secured by the series condenser C_1 of Fig. 43, for by the use of this condenser a much smaller control current is required to effect a given variation in antenna current. If the capacitance of C_1 is chosen to neutralize the inductance of the windings A for some definite value of excitation current in the control coil B, the impedance of the circuit C_1, A, becomes a minimum. The impedance at any lower excitation is determined by the difference between the inductive reactance of the amplifier coil and the capacitive reactance of the series condenser. However, the smaller this difference the lower will be amplifier excitation which gives minimum impedance and therefore minimum alternator voltage.

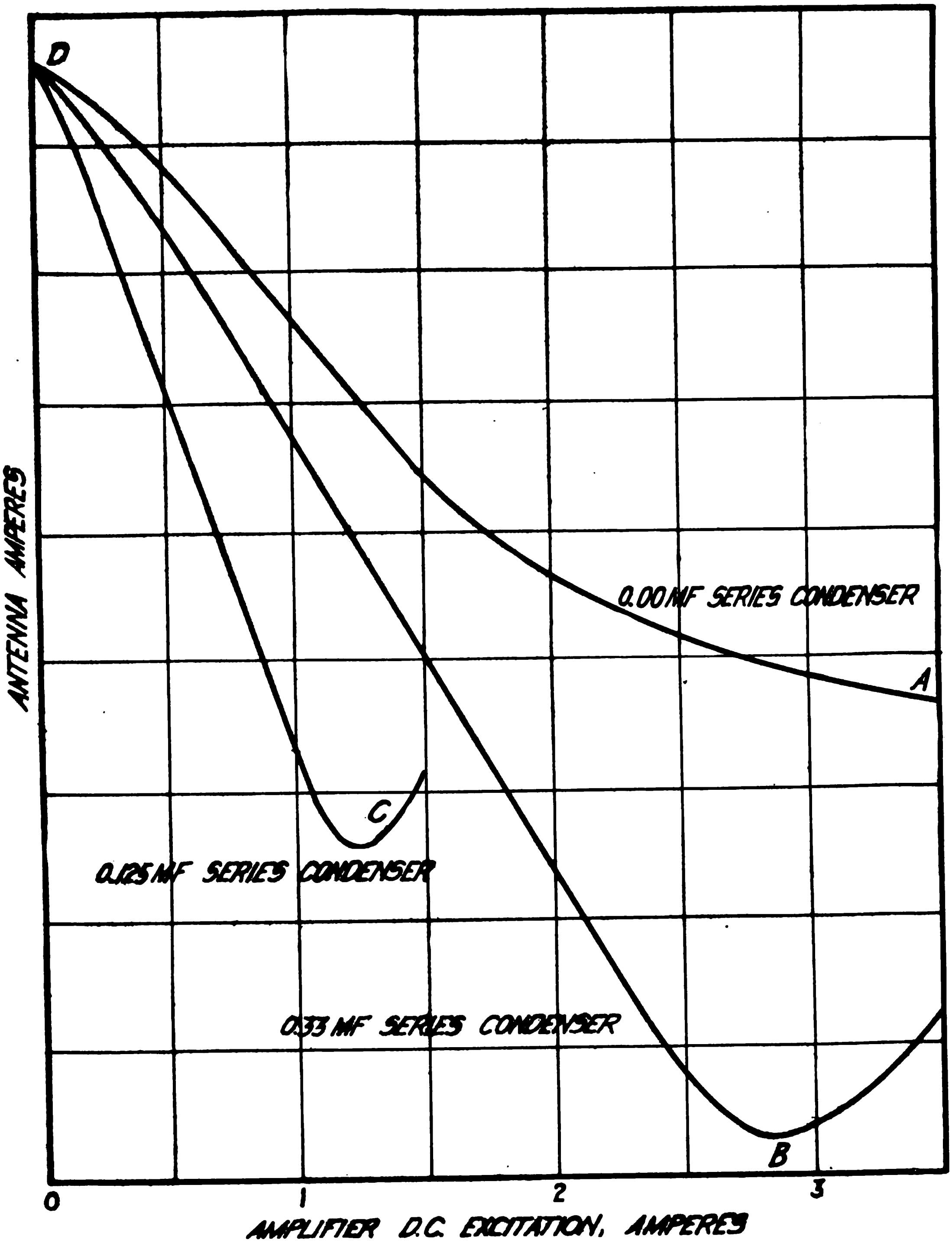


FIG. 42.

Control Characteristics of the Magnetic Amplifier.

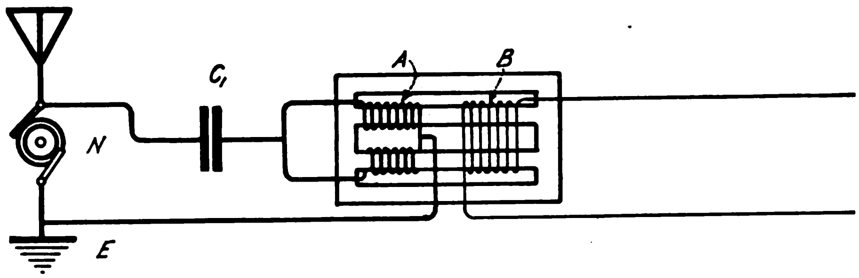


FIG. 43.
Magnetic Amplifier with Series Condenser.

The increase in sensitiveness obtained from the series condenser is well shown by the curves B and C of Fig. 42. The curve A, as already mentioned, shows the antenna currents for different control currents, without the series condenser C_1. The curve B shows the control obtained with a series condenser of 0.33 mfd. and the curve C with 0.125 mfd. The curve B shows almost complete modulation of the antenna current. Although it is a matter of principal importance in radio telephony it is pointed out here that the curve B indicates a linear proportionality between control and antenna currents almost throughout its range. This is an essential requirement for satisfactory speech reproduction in telephony. The excessive control indicated at the right of point B with the larger values of control current is a condition easily avoided in practice.

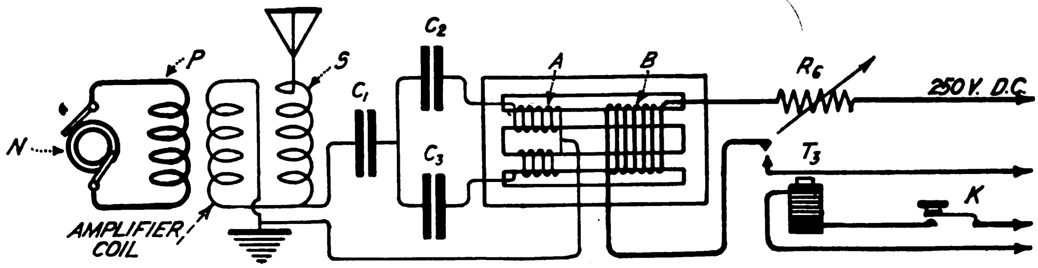


FIG. 44.
Magnetic Amplifier with Series and Short-Circuiting Condensers.

In the final form of the magnetic amplifier, the condensers C_2 and C_3 are inserted in the amplifier windings A, as shown in Fig. 44. Their function is as follows: If telegraphic currents were introduced into the control coil B with the condenser C_2 and C_3 absent, a short curcuit current would flow between the branches of A without producing any flux variations to the radio frequency current. This, however, is prevented by choosing values of C_2 and C_3 to have a low reactance to the radio frequency currents and a high reactance to the audio frequency currents. These condensers have no appreciable effect upon the tuning of the amplifier circuit.

In the commercial set the constants of C_1 are selected for the particular frequency at which operation is to take place, and it is therefore only necessary to vary the control current in the coil B

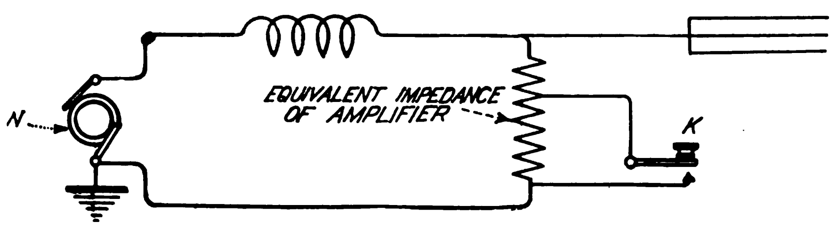


FIG. 45
Equivalent Circuit of Fig. 44.

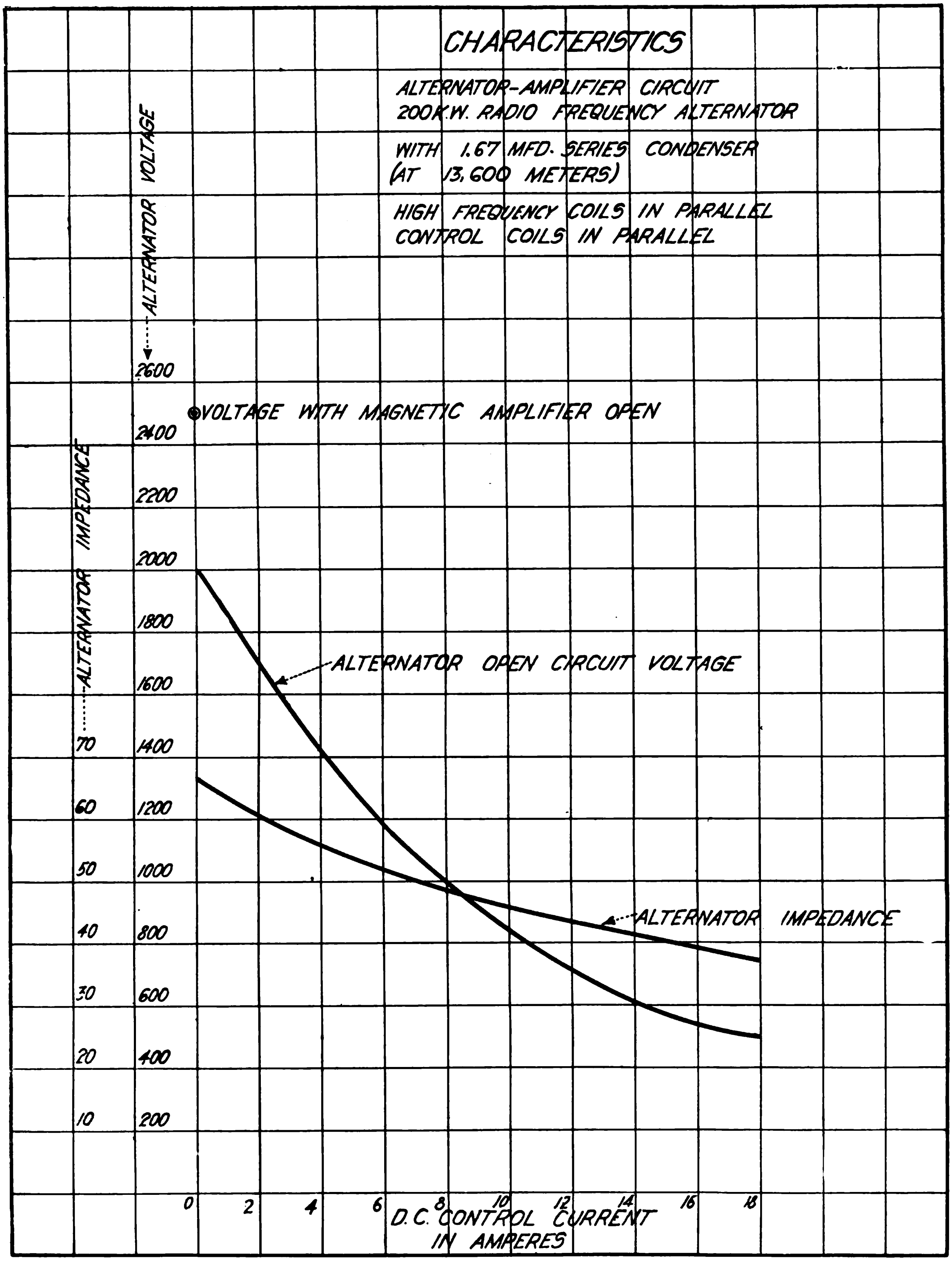


FIG. 46.

Characteristic of Alternator-Amplifier Circuits, 200 Kilowatt Alexanderson Radio Frequency Alternator.

until the most complete modulation of the antenna current is obtained. In the event that the alternator is worked at some frequency different from that originally contemplated, a value of C_1 can be found for some definite value of control current in B, at which a minimum impedance in the amplifier coils is obtained.

In summary of the foregoing the equivalent circuit of Fig. 44 will be seen to be that of Fig. 45 where the telegraphic key K when closed reduces the impedance of the amplifier and therefore the impedance of the amplifier-alternator circuit. This simultaneously detunes the antenna circuit and reduces the alternator voltage.

Characteristic curves showing the variation of alternator voltage, and change of alternator-amplifier impedance with different values of current in the excitation winding (for the standard 200 K.W. set), are presented in Fig. 46. Thus with zero current in the control circuit the alternator open circuit voltage is 2,000, and approximately 500 volts with 18 amperes in the control coil. Similarly with zero current in the control coil the alternator impedance is 67 ohms and it drops to 37 ohms with 18 amperes in the control coil. Theoretical considerations of the circuits involved and actual test show that this drop in alternator impedance reduces the alternator voltage and detunes the antenna system to the extent that no more than 9% of the total normal current flows in the antenna system (when the current in the control winding is zero.)

In explanation of the control current of 18 amperes (fed by a 250-volt source) in the case of a 200 K.W. installation, it may be said that the same variation of alternator output might be obtained with much smaller values of control current. The larger value is purposely used to permit rapid signalling, that is, it permits the magnetic amplifier to function without lag.

RADIO TELEPHONY

Since the magnetic amplifier provides a linear control of the antenna current and functions with small values of control current, it is applicable as a modulation device in radio telephony. When telephonic currents of suitable amplitude are passed through the control coil B, Fig. 44, similar variations of the antenna current will be obtained, provided the amplifier characteristics are selected to give linear proportionality; otherwise inaccurate speech reproduction will result. It has been amply demonstrated in practice that such characteristics are readily obtained from the amplifier. Thus the curves B and C, Fig. 42, both show the desired linear proportionality between control currents and antenna currents, but the curve B shows the most complete modulation of the antenna input.

The perfection of control provided by the magnetic amplifier has been well demonstrated in a series of tests made on the 50 K.W. Alexanderson alternator. With a telephonic control current varying in amplitude by 0.2 ampere, the antenna current was changed from 5.8 to 42.7 K.W., a variation of almost 37 kilowatts.

Fig. 47 is an oscillographic record taken on the 200 K.W. set at New Brunswick, N. J., with Secretary Daniels, of the U. S. Navy Department, at Washington, D. C., speaking to President Wilson aboard the U. S. S. George Washington at sea. The satisfactory operation provided by the amplifier is here again well demonstrated.

When the Alexanderson System is used in radio telephony, the control circuit of the amplifier is placed in the output circuit of a bank of vacuum valve amplifiers. The input circuits of the amplifier bank are controlled by three preceding steps of vacuum tube amplifiers, which in turn are actuated by the microphone.

In a number of experimental tests made with the telephone set at New Brunswick, the voice

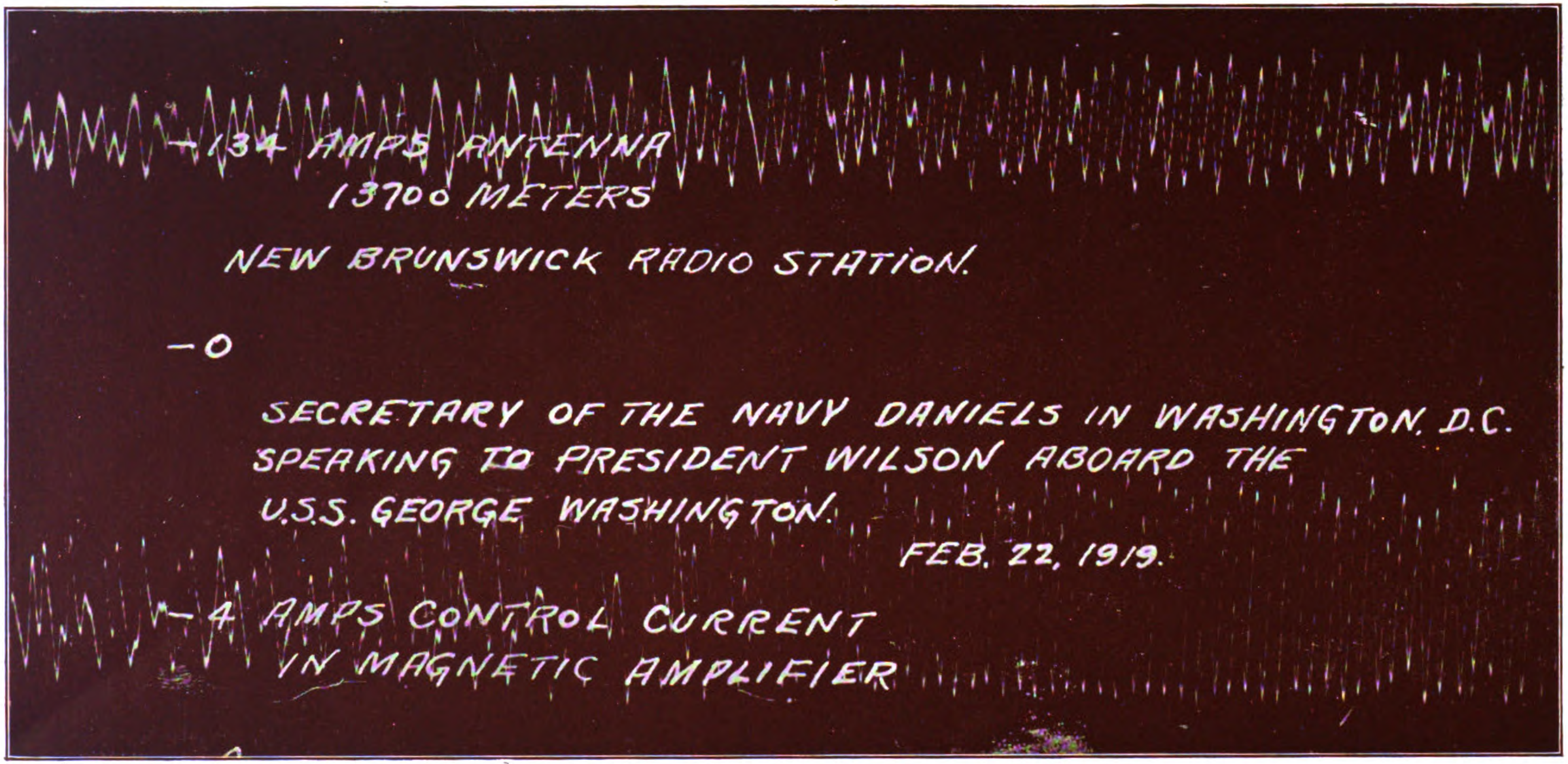


FIG. 47.

Oscillograms of Control and Antenna Currents Using a 200 Kilowatt Alexanderson Alternator Set for Oversea Radio Telephony.

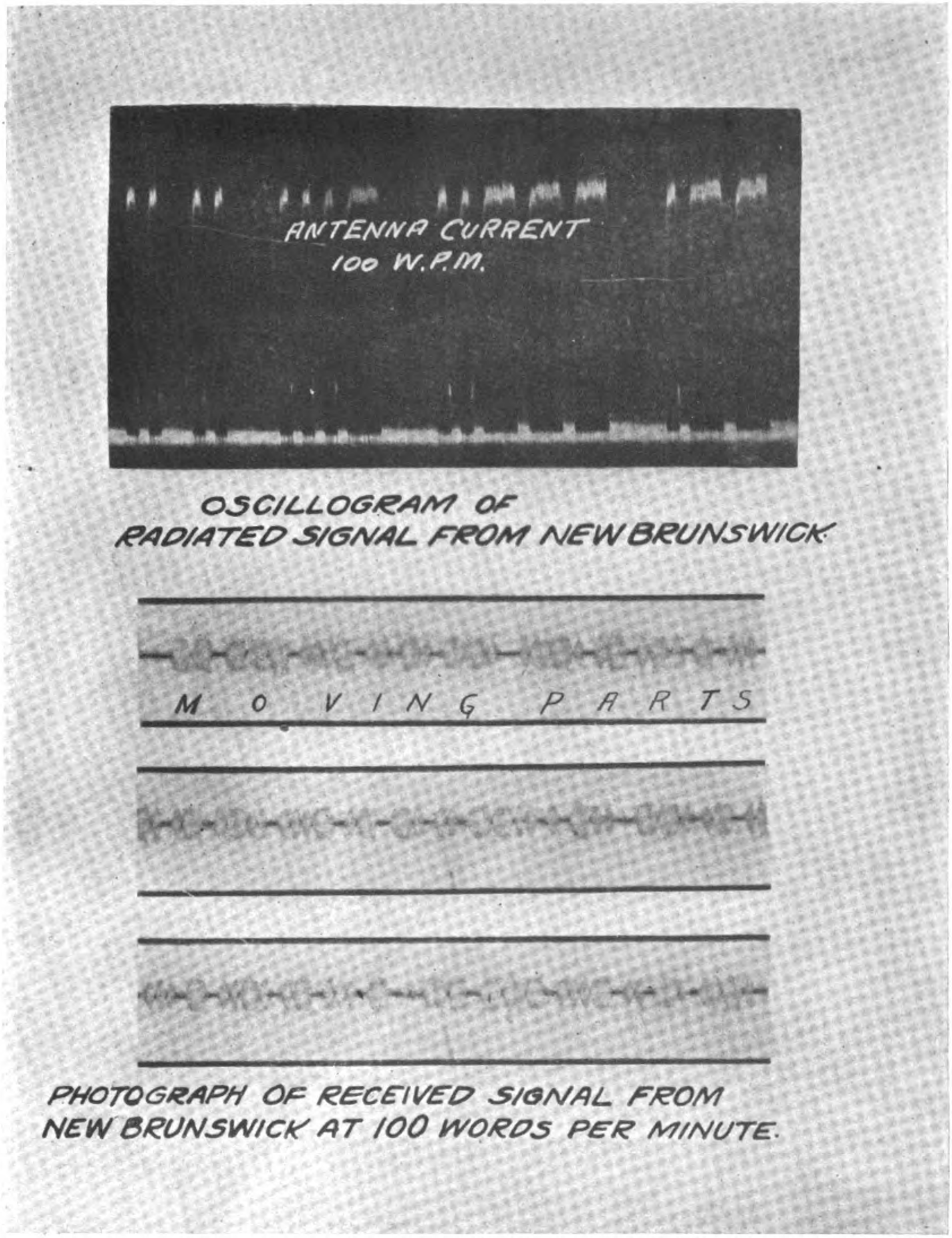


FIG. 48.
Oscillogram of Transmitted Signal and Photographic Record of Received Signal from New Brunswick Station at 100 Words per Minute.

was projected to European stations. At distances up to 2,500 miles very satisfactory results were obtained. The eventual use of the Alexanderson System for commercial long distance radio telephony can be predicted with considerable confidence.